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A WATER QUALITY MODEL FOR A CONJUNCTIVE SURFACE-GROUNDWATER SYSTEM

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Emphasis was placed on the modeling of agricultural pollution. For this reason, nitrogen and phosphorous were the main substances considered. The selection of the Lake Apopka basin in Central Florida as the study area was made in accordance with these project goals. The data base for this basin was limited, but better than that for other candidate areas in Florida. However, this data base appeared typical of that available to engineers in the analysis of a practical problem. The scope of this particular study precluded additional sampling. Current data limitations precluded a complete verification of the model. However, various general conclusions could be drawn. In the future, the formulation could be viewed as an instrument for structuring data gathering efforts. (EPA)

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A WATER QUALITY MODEL FOR A CONJUNCTIVE SURFACE-GROUNDWATER SYSTEM

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Emphasis was placed on the modeling of agricultural pollution. For this reason, nitrogen and phosphorous were the main substances considered. The selection of the Lake Apopka basin in Central Florida as the study area was made in accordance with these project goals. The data base for this basin was limited, but better than that for other candidate areas in Florida. However, this data base appeared typical of that available to engineers in the analysis of a practical problem. The scope of this particular study precluded additional sampling. Current data limitations precluded a complete verification of the model. However, various general conclusions could be drawn. In the future, the formulation could be viewed as an instrument for structuring data gathering efforts.

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SECTION I

CONCLUSIONS

The results indicate that it is feasible to model a conjunctive surface-groundwater system. Current data limitations in the rather typical data base available for the study area precluded a complete verification of the model. However, the formulation can be used as a guide for data collection in this and other similar areas.

While it is desirable to conduct modeling efforts using a systems approach, it appears that a close integration of the various individual programs would be premature. In their present relatively independent status, the programs are more accessible for the introduction of improvements. Also, the high computation cost and programming complexities inherent in a fully interfaced approach seem to be unwarranted in the light of present need for additional data.

Much remains to be accomplished in the usage and interpretation of agricultural information affecting water quality. A better quantitative insight into the mechanisms of various processes (e.g. soil erosion, nutrient reactions in the soil) would provide direction to future sophistication in modeling efforts.

Regarding the study area (Lake Apopka basin, Florida), overland flow nutrient contribution to the lake appears to be of little significance. Subsurface seepage of fertilizer nutrients from the sandy soils areas to the lake is likely to be small, due to the groundwater flow conditions, which tend to transport substances downward and not laterally. Using the available data, computations indicate that more comprehensive simulation of the muck farms would require additional information on flow rates and on the seemingly important muchanism of nutrient release by the soil. The predicted movement of substances within the lake is slow, and quality calculations would be much improved by field data allowing proper consideration of source/sink effects involving the bottom sediments.

Considering source-sink effects in subsurface water, some preliminary modeling was conducted for the unsaturated zone (e.g. nutrient release by muck soil). However, inclusion of source/sink calculations in groundwater would have required usage of the scarce data available in the literature for dissimilar areas. It was felt that further effort in this regard would not be realistic and would detract from efforts in other subsystem models.

SECTION II

RECOMMENDATIONS

In formulating needed modeling improvements, it is suggested that first each model be considered individually. These modifications should be carried out in conjunction with data gathering efforts. Work on computer programming of interfacing aspects should follow the verification and calibration processes.

For improvements in describing surface and shallow subsurface phenomena, it would be worthwhile to further examine the watershed model developed recently by the Agricultural Research Service (1971). This ARS model does not include quality calculations, but its flow routines incorporate numerous agricultural features (e.g. soil medium discontinuities and the effect of plants) which are pertinent to sediment transport (thus, also to transport of nutrients).

In agricultural areas where groundwater flow conditions change slowly, it seems that the vertical, two-dimensional groundwater model applied to selected cross-sections provides satisfactory insight. Careful consideration should be given to computation cost prior to utilizing a three-dimensional formulation. Additional data on source/sink processes in groundwater are an essential requirement for better predictions.

The receiving model, used in connection with the muck farms and Lake Apopka, is quite flexible and versatile, and should be widely applicable. Its predictive quality could be improved by data allowing proper consideration of nutrient cycling phenomena, especially those involving sediments.

It appears that quality data collection work in the Lake Apopka basin should center on the release of nutrients by the muck soil and on sediment-water interchanges in the lake. Better information on the various flows (i.e. drainage pumpage and irrigation records) occurring between the lake and the muck farms would allow more precise answers on nutrient fluxes.

SECTION III

INTRODUCTION

OVERVIEW

In recent years, increasing pressures toward efficient decision-making in water pollution control have created the need for improved pollutant routing models. Such mathematical models help determine cause and effect relationships between sources of pollutants and the ensuing concentrations at various locations in a basin. A better knowledge and understanding of these relationships should, hopefully, promote the expenditure of economic resources where they are most needed.

A basin-wide study of water quality must take into account the various hydrologic processes such as rainfall, runoff, infiltration and groundwater flow that occur in nature. These processes determine the spatial and temporal distribution of water in the basin. As the water moves within the system, it is subjected to a set of physical, chemical and biological driving forces which affect its quality characteristics.

Numerous models have already been developed to simulate the above hydrologic and water quality processes. However, many of these formulations have been produced by researchers working independently within their own area of interest, such as meteorology or agriculture. For this reason, much work remains to be done in modifying these individual models to render them useful for the unifying purpose of predicting water quality changes in a basin. It also is apparent that much remains to be accomplished in the area of interfacing these models once they are made compatible.

The objectives of this investigation were two-fold: improving existing formulations for the various processes occurring in a basin and developing a methodology for interfacing these formulations. Additional information on these goals is presented following a description of the physical system.

DESCRIPTION OF THE PHYSICAL SYSTEM

Figure 1 constitutes a vertical cross-section of a basin, and indicated therein are some of the physical features and hydrologic processes which are of interest in this study. The movement of water in the system can be predicted using various hydraulic relationships. These relationships utilize values of initial and boundary conditions (e.g., rainfall) to determine the magnitude and direction of flow velocity at different locations. Associated with the movement of water are physical, chemical and biological processes which affect its quality. The processes acting upon a given particle of water are largely determined by the particle's location in the system. For instance, scouring and deposition are phenomena occurring in surface runoff, while dispersion may occur in both surface and groundwater flow.

A common approach was taken in modeling the surface, unsaturated flow and groundwater phenomena: the flow or quantity aspects were simulated first, followed by the water quality aspects. At each time step, the velocities at various physical locations were determined from the hydraulic formulations. The calculated velocity field was then used as input to the water quality models, which routed the movement of pollutants through the system. This sequential approach was required because certain water quality phenomena (e.g., dispersion) are affected by velocity.

From Figure 1 it can be seen that the path of any particle of water may cross different regions which, in turn, involve different models. This fact points out the need to formalize methods for utilizing these models sequentially and for transmitting information from one model to another. Some of these interfacing aspects are depicted in Figure 2. The boxes in this figure represent physical locations in a basin, which may be sources or sinks of pollutants. The arrows denote movement of these pollutants among the various locations. Two major items are considered in routing this movement: flows and pollutant concentrations. A more detailed explanation of the interfacing methodology is presented later.

OUTLINE OF WORK

The resulting computer models were tested in the Apopka basin, a predominantly agricultural area in Central Florida. The location of this basin is shown in Figure 3. In this report, discussions involving the development and discussion of mathematical techniques precede those pertaining to the application phase of the study.

For organizational purposes, both the hydrologic and water quality models were classified according to the major physical location where they occur, namely: surface, unsaturated soil zone and groundwater

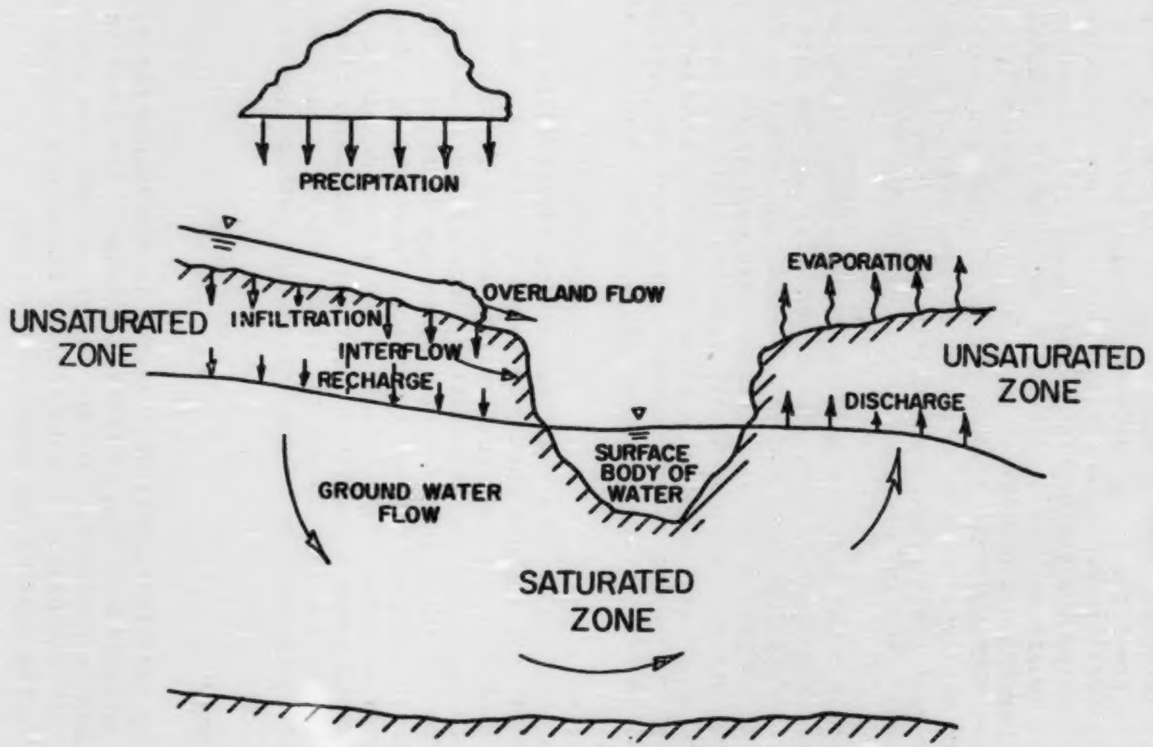

PRECIPITATION
OVERLAND FLOW
EVAPORATION
UNSATURATED ZONE
INFILTRATION
INTERFLOW
RECHARGE
UNSATURATED ZONE
DISCHARGE
SURFACE BODY OF WATER
GROUND WATER FLOW
SATURATED ZONE

Figure 1. Vertical cross-section of a typical basin.

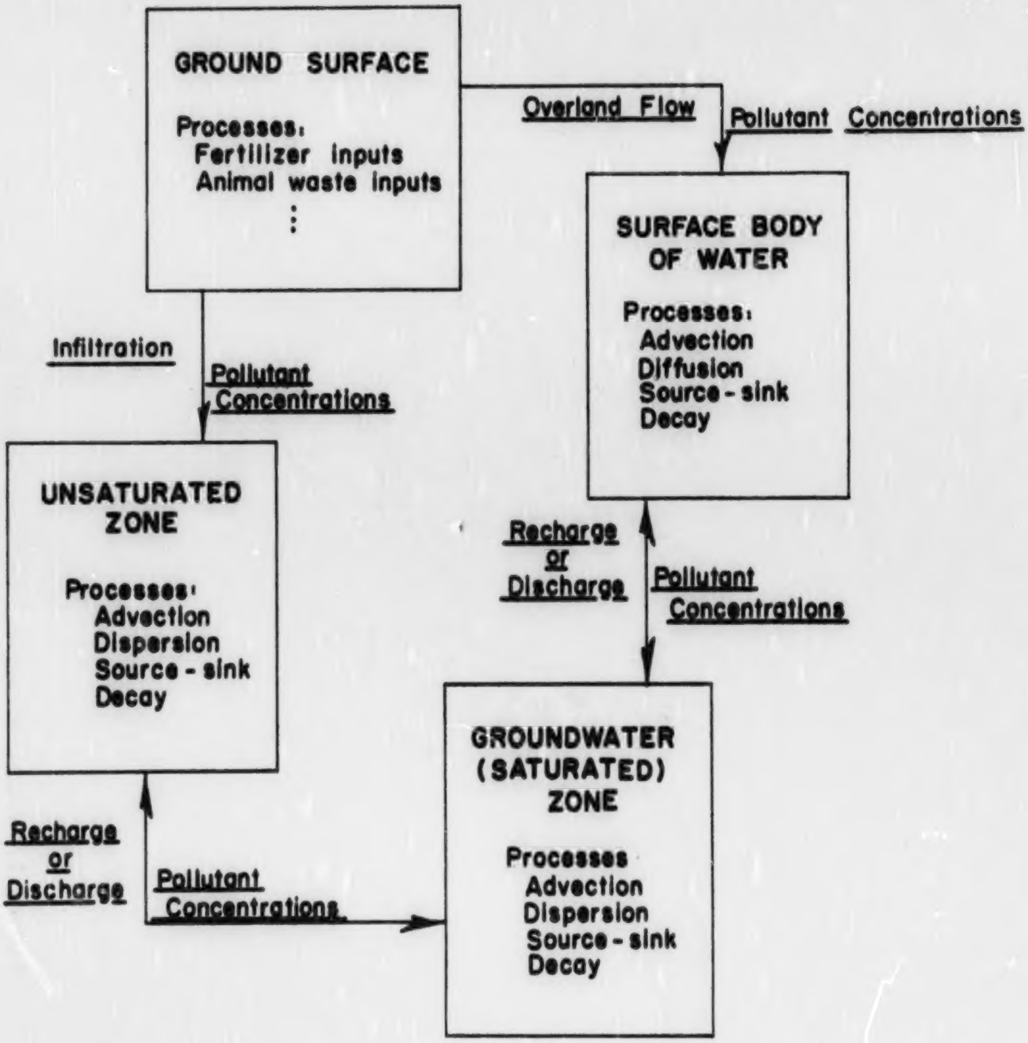

GROUND SURFACE
Processes:
Fertilizer inputs
Animal waste inputs
⋮
Overland Flow
Pollutant Concentrations
SURFACE BODY OF WATER
Processes:
Advection
Diffusion
Source - sink
Decay
Infiltration
Pollutant Concentrations
UNSATURATED ZONE
Processes:
Advection
Dispersion
Source - sink
Decay
Recharge or Discharge
Pollutant Concentrations
GROUNDWATER (SATURATED) ZONE
Processes
Advection
Dispersion
Source - sink
Decay
Recharge or Discharge
Pollutant Concentrations

Figure 2. Linkages involving various physical locations and mathematical models.

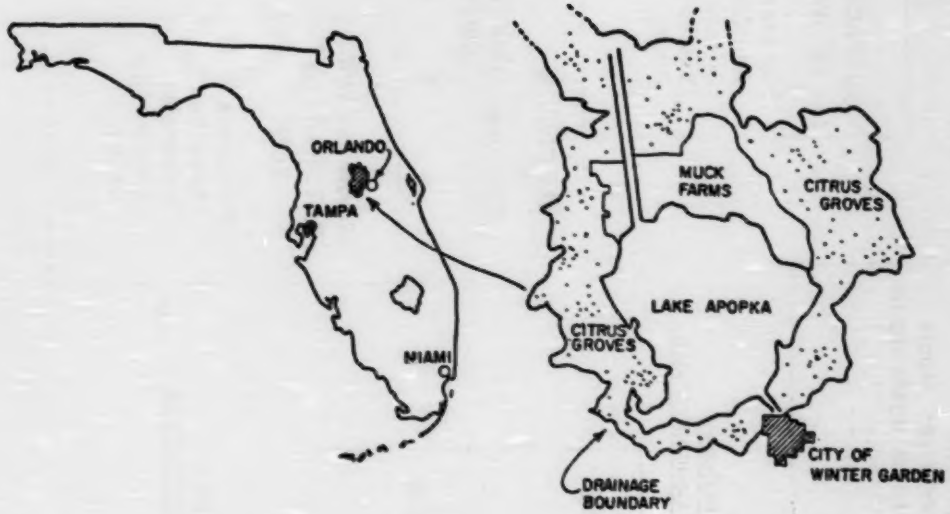

ORLANDO
TAMPA
MIAMI
MUCK FARMS
CITRUS GROVES
LAKE APOPKA
CITRUS GROVES
CITY OF WINTER GARDEN
DRAINAGE BOUNDARY

Figure 3. Location map of the Lake Apopka basin.

zone. One section is devoted to each of these three classes, in the order above. Each section contains a brief survey of the pertinent literature (for a more comprehensive review refer to Perez's dissertation (1972)) and discussions on the selection of the formulations used and the corresponding modifications introduced. In most cases, mathematical complexities and lengthy derivations are relegated to the appendices which also include sample calculations. In the discussion of all major formulations, the consideration of flow or quantity processes will precede that of water quality aspects.

Following the three sections covering the individual models, a section is provided to discuss the interfacing methodology. Subsequently, the study area description and other application aspects are presented. The last section is devoted to the results and conclusions.

Although the methodology developed herein is intended to be applicable to any basin, primary emphasis in this study is placed on agricultural pollution and on the routing of nitrogen and phosphorous. Thus, water quality discussions in the following chapters will be centered on these two substances. Also, discussions on agricultural pollution calculations, data usage and other matters related to agriculture are included in various appendices. It is strongly suggested that before readers attempt to follow the sample model calculations and computer program summaries provided in Appendices A, B and C, they be familiar with the respective mathematical formulations explained in Sections IV, V and VI.

SECTION IV

SURFACE WATER MODELS

GENERAL DISCUSSION

Various hydrologic phenomena occur on the surface of any basin, namely: (1) precipitation, (2) evaporation, (3) evapo-transpiration, (4) overland flow or runoff and (5) flow in surface bodies of water (e.g., lakes and streams). Consideration of the first three phenomena above, and their associated water quality processes, is usually not a major problem for two reasons. Firstly, better data generally exist for these items than for other surface and subsurface phenomena. Secondly, their computations and mathematical formulations are relatively simple.

For these reasons, the attention paid in this study to precipitation, evaporation and evapo-transpiration is somewhat limited. In this section, brief literature reviews and discussions on the significance of these topics are included. In the application phase of the project, the available data were coupled with simplifying assumptions about the behavior of these processes.

On the other hand, the processes of runoff and flow in surface bodies of water are covered extensively herein. Consideration of these processes begins with a discussion of the types of variables involved and a review of the literature. The discussion then covers basic formulations and modifications used in this study.

The following subsections cover each of the five hydrologic phenomena listed above, in the same order. For each phenomenon, discussions on quantity aspects generally precede those involving water quality.

PRECIPITATION

Quantity Aspects

The phenomenon of precipitation includes both rainfall and snow. A recent publication by the U. S. Department of Agriculture and Department of Commerce (1969) provides monthly precipitation probabilities for various climatic divisions in this country. In many states, such as Florida, the regional and temporal variability of precipitation has warranted the compilation of frequency data (Butson and Prine, 1968, U. S. Weather Bureau, 1961).

Even within a specific geographic region, the measurements at various gaging stations have been found to differ significantly, depending upon the type of storm and the local topographic conditions. Consequently, the average precipitation on a given area is usually computed by assigning certain weighting factors, commonly known as Thiessen weights, to the measurements at the various gages (Linsley and Franzini, 1964). A computerized method has been developed by Diskin (1970).

Another application of computer models in hydrology is in the area of rainfall synthesis, in which the production of synthetic or artificial records is accomplished through the coupling of actual records and statistical techniques (Yevdjevich, 1972). A model for synthetic streamflows has been discussed by Fiering (1971).

It might be pointed out that while the studies discussed above apply to precipitation in general, the behavior of snow after it reaches the ground differs markedly from that of rainfall (Eagleson, 1970). Much work has already been performed in the analysis of the meteorological variables affecting the behavior of snowpack and the production of snowmelt. For this reason, these relationships are not considered in this investigation. Furthermore, the location of the study area in Florida precludes any verification of snowmelt formulations.

Quality Aspects

The concentration of any substance in rainfall depends upon a myriad of factors. One of these is the intensity-duration relationship of the storm. As a general rule, the concentrations measured in the rain decrease exponentially with time. The first rain droplets remove a large amount of gaseous and particulate matter from the atmosphere, and carry them downward. The availability of these substances in the atmosphere then decreases, and therefore their presence in subsequent rainfall becomes more scarce. Gambell and Fisher have found that the total rainfall relationships vary with type of storm.

Another major factor affecting the amounts of atmospheric constituents in rain is the rate at which they are made available by their different sources. These sources can be natural or man-made processes. For instance, decreasing Cl^- concentrations in the air with increasing distance inland suggest to some investigators that the main source of this ion is sea water, swept upward by the winds (Weibel et al., 1966). The presence of various forms of nitrogen in the atmosphere stems from organic decay processes in the surface of the earth, photochemical reactions in the atmosphere and several human activities such as application of fertilizers. Weibel and co-workers have deemphasized the significance of the formulation of NO_3^- from lightning. Chemical reactions within the atmosphere are illustrated by the conversion of NO_2^- to NO_3^-.

Transport processes also play an important role in determining the availability of substances in the atmosphere. Pesticides such as DDT, for example, have been found to be carried by the wind for long distances (Weibel et al., 1966). These pesticides can exist in vapor form or they can be adsorbed on particulates. Their physical state affects their diffusion rates.

In short, the concentrations of substances in rainfall are influenced by man, physical and chemical reactions and meteorological conditions in the atmosphere. Unfortunately, these factors are not well understood from a quantitative standpoint. Consequently, the development of mathematical models or even substantive regression equations to describe these processes would appear to be premature.

Instead, the approach taken in this study is to demonstrate the use of rainfall quality data collected in the vicinity of the study area. The quality of rainfall should not be ignored in this or any other basin. Weibel et al. (1966) for instance, have found that ammonia and nitrate concentrations in rainfall are sometimes higher than the threshold values for algal nuisances.

EVAPORATION

Quantity Aspects

The loss of water from surface bodies to the atmosphere is generally important in a basin-wide hydrologic balance. Evaporation computations are applied to relatively large lakes and streams which exist on a perennial basis. Temporary or small accumulations of water on soil fall within the realm of evapo-transpiration formulas. These formulas are discussed in the following subsection.

It is of interest to explore first the types of variables involved in the mechanics of the evaporation process. This discussion will be followed by an examination of field measurement considerations, and finally by a discussion of water quality effects.

The basic relationship governing the rate of evaporation is (Eagleson, 1970):

$$E = -K \frac{de}{dz} \tag{1}$$

where E = evaporation rate, in/hr

K = transfer coefficient, 1/hr

e = vapor pressure, in

z = elevation, in

The value of the vapor pressure is in turn affected by other variables such as salinity and total atmospheric pressure. In fact, the interactions between meteorological variables are so complex that it is difficult in practice to compute the effect on vapor pressure of any single parameter.

Commonly, evaporation estimates are made in the field using pans. This process involves three phases. First, the actual pan evaporation losses are measured and recorded. Secondly, the basin-wide evaporation losses are estimated from measured values of all the other remaining variables in the water budget. Finally, a pan coefficient (proportionality factor) is found which will best relate the two results (Thornthwaite and Mather, 1955; Eagleson, 1970; Kohler, 1954).

Since the primary goals of this investigation were to emphasize the regional water quality transport processes, no mathematical formulations were attempted herein. The use of pan data in actual evaporation computations is discussed later.

Quality Aspects

Water quality effects of evaporation are basically the following: (1) concentration changes in the water produced by changes in volume, (2) evaporation of non-ionic substances and (3) changes in the heat content of lakes and streams, which affect chemical and biological reaction rates. The first item can be handled adequately by simple mass-balance computations and therefore one may proceed to examine the remaining two items.

Ions tend to remain in solution and do not escape with the evaporating water. The only significant non-ionic substance subject to evaporation is ammonia (Stratton, 1969). The relative amounts of the gaseous and ionic forms of ammonia are controlled by the equilibrium reaction

$$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^- \qquad (2)$$

Thus as the pH increases, the amount of NH_3 dissolved in water also increases. Ammonia will evaporate if its partial pressure in the water is greater than that in the atmosphere. For this case, a first-order reaction equation has been proposed to describe the transfer.

Predictive efforts attempted by Stratton were not very successful, however.

Regarding heat losses from impoundments due to evaporation, one widely used technique is that developed by Edinger and Geyer (1965). Huber and Perez (1971) discuss other formulations, including Kohler's (1954) relationship based on equation (1). In areas where evaporation measurements are available, a simpler calculation may be conducted using the amount of water lost and the latent heat of vaporization. Evaporative heat losses will cause temperature drops in the water. As a rule, chemical and biological reaction rates tend to decrease after such losses.

EVAPO-TRANSPIRATION

Quantity Aspects

The transfer of water from the soil and plants to the atmosphere is known as evapo-transpiration. Due to the great variety of soil and plant characteristics, the direct computation of this transfer can become burdensome. For this reason, hydrologists often compute all other items in the water budget first and then obtain evapo-transpiration by subtraction. This is generally a satisfactory method when the land use patterns in the basin are essentially static. If this is not the case, particularly if heavy irrigation is contemplated, a direct approach is preferable. Some direct methods have been developed by Penman (1948), Thornthwaite and Mather (1955, 1957) and Freeze (1967). In 1962, Blaney and Criddle dealt with irrigation water requirements, which are significantly affected by evapo-transpiration.

Numerous studies are available on the estimation of evapo-transpiration rates for specific geographic regions. In the State of Florida, one recent paper has been that by Hashemi and Gerber (1967) on evapo-transpiration from citrus areas. Another investigation, carried out by Stewart et al. of the USDA Agricultural Research Service (1969), deals with the effect of plant density and water table depth on evapo-transpiration. As in the case of rainfall and evaporation, little emphasis was placed in this study on the use of sophisticated formulations for evapo-transpiration.

Quality Aspects

The water quality implications of evapo-transpiration cover basically just one of the factors previously mentioned in connection with evaporation from impoundments: the loss of ammonia to the atmosphere. Its extent would be largely determined by the pH of the water in the soil and in plants. Little information is available on this subject.

OVERLAND FLOW (RUNOFF)

General Considerations

When rainfall arrives at the ground surface, a portion of it penetrates the soil, another portion evaporates and the rest becomes overland flow or runoff. This separation process is quite complex, and reasonable success in simulating it necessitates proper interfacing of the mathematical models for the individual phenomena involved. For instance, data such as ponding depths and infiltration rates are commonly used in both runoff and infiltration formulations.

Numerous overland flow models are available in the literature, ranging from the theoretical to the semiempirical. A brief review of the major types of models is given below. Additional discussion of these may be found in Perez's dissertation (1972).

LITERATURE REVIEW

Background

The characteristics of the numerous available runoff models are so varied that an effective system of classification for purposes of discussion is rather elusive. Instead, the approach taken herein is to present some representative models in the approximate chronological order in which they were created.

Quantity Aspects

Much of the early work in runoff modeling was prompted by developments in the understanding of the infiltration process as presented by Horton (1940), Phillips (1957) and Holtan (1961). In 1964, Overton compared the formulation of the above investigators and summarized their similarities. It recent years, other infiltration formulations (Freeze, 1969) have emphasized a numerical solution involving Darcy's Law. These and other aspects are covered in greater depth in the chapter on unsaturated zone models.

Infiltration relationships are now being combined with surface flow formulations to produce comprehensive watershed models, e.g., Holtan and Overton (1964), Huggins and Monke (1968) and Onstad and Brakensiek (1968). In 1970, Sinha and Lindahl presented a paper on an operational watershed model which applied Nash's (1957) technique for routing overland flow through surface reservoirs. In a related paper, Glymph, Holtan and England (1971) discussed the watershed model developed by the Agricultural Research Service (USDA) and particularly its application to various study areas in the United States.

Much research has been conducted recently in the areas of hydrograph analysis and optimization of hydrologic parameters (Overton, 1968). Also, James _et al_. (1970) developed a self-calibrating version of the Stanford Watershed Model (Crawford and Linsley, 1966), and titled it the Kentucky Watershed Model. The latter formulation is written in FORTRAN language. One drawback of both the Stanford and Kentucky models is that they utilize a large number of variables, many of which cannot be measured directly.

Most of the above mentioned models were intended for application in predominantly rural areas. However, some models have been developed which are better suited for urban situations. One example is the Stormwater Management Model, formulated by the University of Florida, Metcalf and Eddy, Inc. and Water Resources Eng., Inc. (Environmental Protection Agency, 1971). Basically, the runoff portion of this model utilizes Manning's equation to compute overland flow and Horton's equation to determine infiltration.

Another significant development in the field of runoff modeling has been the use of the kinematic wave approach along with the method of characteristics (Eagleson, 1970). As its name suggests, this approach determines the propagation of flood waves or disturbances down a catchment. A characteristic is defined as the path, in the horizontal and vertical directions, traveled by a given disturbance. Eagleson's analytical formulation assumes constant rainfall and infiltration. Improvements have been proposed by Eagleson and Maddaus (1969), Bravo _et al_. (1970) and Harley, Perkins and Eagleson (1970).

Quality Aspects

Two main processes affect runoff water quality: (1) uptake of soluble substances by the water, and (2) scouring and deposition of solids. Very few of the overland flow models contain any water quality formulations. One exception is the Stormwater Management Model. The relationships utilized in this model are rather simple, but they are commensurate with the accuracy of the water quality data that are typically available.

Selection of Runoff Models

Two basic conditions were utilized to select the types of runoff models to be used in this study. The first was that the number of variables should be small, and just sufficient to properly represent the natural system. The purposes of this condition were to avoid the use of extraneous variables with little physical significance and to minimize computation time. This condition eliminated both the Stanford and Kentucky models from use in this investigation. Since the emphasis herein is on development of a methodology, it was thought that the calibration and modification of either of these models would be cumbersome and lie beyond the overall project objectives.

The second condition used was the availability of water quality formulations in the runoff models considered. This condition was seldom satisfied, as mentioned above, and therefore the relative ease with which quality aspects could be added to the available quantity models was investigated. As a result, the watershed models of the type developed by the Agricultural Research Service were eliminated from consideration for use. This decision was made with some reluctance since these model types, especially the ARS model (Agricultural Research Service, 1971), contain many desirable features. They are based on data collected routinely by agricultural agencies, such as soil characteristics, and their results have been verified in practice. However, the present structures of these models are not well-suited for the systematic routing of pollutants in time and space. It was felt that the changes required to achieve this purpose would extend beyond the scope of this study.

In addition to these two conditions, another factor was taken into account: the applicability of the available models to predominantly urban or rural situations. In view of the lack of a general model to cover both cases, and the apparent difficulties in developing one, the decision was made to use two runoff models in this study.

The Runoff portion of the Stormwater Management Model was selected for application in urban areas and in agricultural regions in which the natural hydrology has been profoundly affected by man. These man-made effects include channelization, pumpage of water and other aspects of artifical drainage. The structural characteristics of this model, such as numbering systems for catchments and corresponding receiving elements, were found to be useful for this type of application. Also the model considers water quality processes.

On the other hand, the modeling of overland flow in natural rural watersheds was carried out using the kinematic wave approach formalized by Eagleson (1970) and others. To apply this method, it is first necessary to divide the study area into catchments. The physical information on these catchments, including length, width, slope and Manning's roughness factor (see Appendix A), is then tabulated. Finally, the model computes the ponding depths, velocities and flows at different locations within the catchments. In the quality calculations, these velocities are used to compute the erosion of soil particles. The uptake of dissolved substances by the flowing water is also considered.

Runoff Portion of the Storm Water Management Model

Background — This runoff model was developed as a part of the comprehensive Storm Water Management Model (Environmental Protection Agency, 1971). The four volume report on this comprehensive model, including a user's manual, provides good documentation on formulas, flowcharts and programming methodologies. For this reason, the discussions below are restricted to the fundamental quantity and quality aspects of this runoff formulation. In its original form, the runoff program simulates the flow over catchments and then into gutters and through pipes, as shown in Figure 4. In this study, only the runoff flow over catchments is of interest and the latter aspects will not be discussed.

Quantity Aspects — The quantity or flow calculations involve the rainfall hyetograph, infiltration rates and runoff flows. A set of sequential computations is carried out at each time step within the period of analysis.

The first operation carried out at a given time step is to add the proper incremental amount of rainfall to each catchment in the study area. Infiltration is then computed for each catchment using one of two possible methods. In the original model, the infiltration rates are calculated from Horton's (1940) exponential function, of the form

$$I_t = f_0 + (f_i - f_0)\, e^{-\alpha t} \tag{3}$$

where I_t = infiltration rate for a given catchment at time t, in/hr

f_0 = final infiltration rate, in/hr

f_i = initial infiltration rate, in/hr

α = a constant, 1/hr

t = time, hr

An alternative approach, used in this study, is to obtain the infiltration values from an unsaturated zone flow model. Specifically, the sequential method utilized herein was to run the infiltration model (see Section V) first, the results of which were stored for later use in the runoff formulation.

The next operation performed by the runoff model is to compare the current water depth (ponding depth) at each catchment to a specified detention depth. If the former exceeds the latter, the outflow rate from the catchment in question is computed using Manning's equation. To satisfy continuity of mass, the Newton-Raphson iterative technique

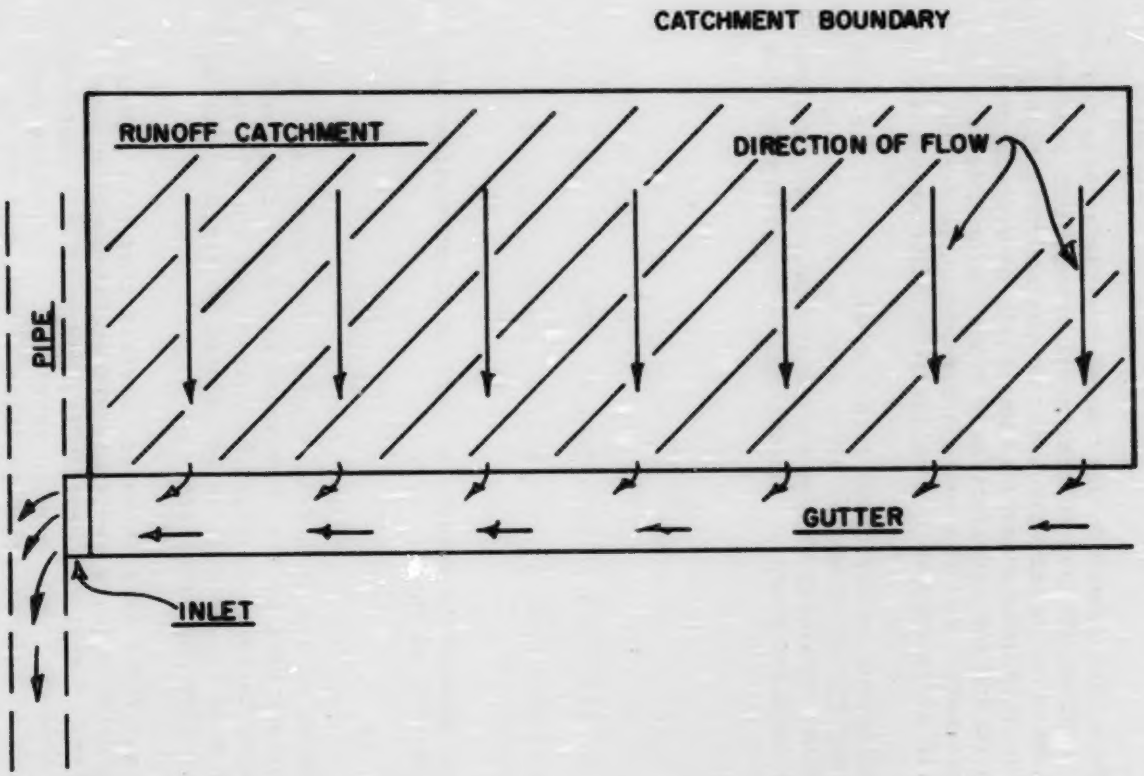

CATCHMENT BOUNDARY
RUNOFF CATCHMENT
DIRECTION OF FLOW
PIPE
GUTTER
INLET

Figure 4. Plan view of application site for runoff portion of the Storm Water Management Model.

is utilized to determine compatible values of water depth and outflow rate. The remaining quantity computations involve flows in gutters and pipes, which are not relevant to this study.

Quality Aspects –
In its original form, the runoff quality model considers three pollutants: suspended solids, BOD and MPN bacterial counts. It assumes that these pollutants are conservative, due to the short transport times involved. In this study, emphasis was given to agricultural rather than urban runoff and therefore only suspended solids were considered. Furthermore, the urban-oriented formulation for this parameter was modified to improve its validity in rural areas.

One basic assumption used in the urban runoff model is that the rate of suspension of any pollutant at any given time is proportional to the mass of pollutant remaining on the ground at that time, thus implying a first-order reaction process. Accordingly, the governing equation becomes

$$P = P_0 e^{-kt} \tag{4}$$

where P = mass of pollutant on catchment at time t, lb

P_0 = mass of pollutant on catchment at the beginning of the rainstorm, lb

k = a rate parameter, assumed to vary in direct proportion to the rate of runoff, 1/hr

t = time, hr

The mass suspension rates computed from equation (4) were then converted to fluxes by dividing by the corresponding runoff flows and applying a conversion factor. It might be pointed out that in an urban area the value of P_0, above, can be related to factors such as land use and street cleaning practices.

An examination of any rural area, however, reveals that some assumptions of the formulation require revision. First, it would appear that the availability of soil for erosion is, for practical purposes, unlimited and not dependent upon erosion rates in the immediate past. Thus, the assumption of a first-order reaction process may not be justified. Also, it seems that erosion would occur only if a critical scouring velocity is exceeded. For these reasons, equation (4) was replaced by other equations. These revised equations are very similar to those developed for the erosion formulation in the kinematic wave model, and to avoid duplication a detailed explanation will be presented in the discussion of that model.

In agricultural areas, the main pollutants usually considered are nitrogen and phosphorous, since these substances are contained in fertilizers. It is interesting to note that recent studies (Stanford, England and Taylor, 1970) indicate that while nitrogen is readily leached through the soil, predominantly in the form of nitrate, phosphorus tends to become fixed to the soil particles, thus becoming available for transport through runoff. Accordingly, only phosphorous is considered in the erosion formulation.

Kinematic Wave Runoff Model

General discussion –

As indicated previously, this model is intended for use primarily in rural watersheds where man's impact, through such features as drainage canals, is of little significance. The mathematical formulation of this model is based on Eagleson's (1970) kinematic wave relationships. For detailed information on this topic, the reader is referred to Eagleson's text.

The main advantage of the kinematic wave method is that it constitutes an analytical solution for a given set of data inputs, and therefore no numerical or iterative techniques are required. However, a price is paid in terms of restrictions that must be placed on the input data. The basic restriction is that the values of rainfall and infiltration be time-invariant. Thus, for any period of study, average rates of these two processes must be used instead of the actual values. As a result, the runoff hydrographs at the various catchments become distorted with respect to their true shape. For the purposes of this study, this distortion was deemed acceptable in view of: (1) the damped nature of rural runoff dynamics and (2) the lack of need to simulate the effect of man-made responses on a short-term basis, such as artifical drainage through canals.

To handle water quality aspects, several additions were made to the original kinematic wave formulation. The most significant of these was the provision for computing flow velocities at various points in each catchment instead of just at the downstream outlets, thus obtaining a better sample of these values. These velocities were then used to compute soil erosion rates.

Quantity aspects –

Preliminary comments.– When rainfall occurs in a given region, its rate often exceeds the infiltration rate into the soil. If this is the case, water will accumulate on the ground surface until the gravitational forces overcome the forces resisting motion, and flow begins to take place. The nature of this flow depends upon the geometry of the terrain. In relatively small and flat catchments, the predominant phenomenon is the thin-sheet flow generally designated as overland flow. Usually, the outflow from these catchments is then routed to small stream channels, and subsequently to higher order streams. In this particular study, the modeling efforts were directed only to these overland flow phenomenon. An illustration of this type of flow and some of the variables affecting it is given in Figure 5.

After consideration of the predominant forces acting on the water, the overland flow formulation becomes that for steady, uniform flow in a wide channel, namely

$$\tau_0 = \gamma y \sin \theta \qquad (5)$$

where τ_0 = bottom shear stress, lb/ft^2

γ = unit weight of water, lb/ft^3

y = water depth, ft

θ = angle of bottom slope

In turn, τ_0 is a function of the Reynolds number and surface roughness factor, in a manner depending upon whether the flow is laminar or turbulent.

The formula used to compute the flow at a given location in a catchment is, then,

$$q = \alpha y^m \qquad (6)$$

where q = flow per unit catchment width, ft^3/sec/ft

m = a constant, found to be 5/3 for turbulent flow

$\alpha = \frac{1.49}{n} (\sin \theta)^{1/2}$ for the above value of m, ft$^{1/3}$/sec

n = Manning's roughness coefficient

The mean velocity of flow (ft/sec) can be obtained by dividing the flow per unit width, above, by the water depth. If this operation is carried out, the resulting expression for velocity becomes

$$v = \alpha y^{m-1} \qquad (7)$$

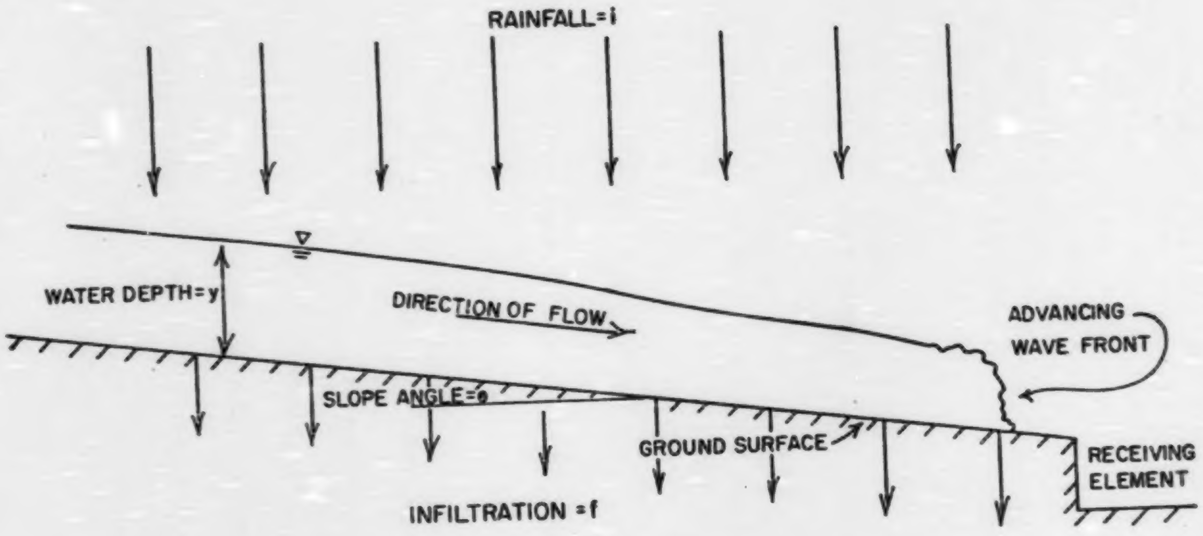

RAINFALL = i
WATER DEPTH = y
DIRECTION OF FLOW
ADVANCING WAVE FRONT
SLOPE ANGLE = θ
GROUND SURFACE
RECEIVING ELEMENT
INFILTRATION = f

Figure 5. Lateral view of overland flow on a catchment.

It follows from equations (6) and (7) that it is necessary to determine the water depth prior to computing velocity and flow. This is a significant factor from the standpoint of structuring the computer program.

The objective of the formulation is basically to predict the velocities at different times and locations in a given area. For this purpose, the overland flow is assumed to have the characteristics of a kinematic wave. The mathematical properties of this wavelike motion are obtained by the method of characteristics. In essence, this technique establishes the path (in time and space) of wave propagation, known as the characteristic curve, along which certain relationships hold. The variable specifically considered in the computer program is y, the flow depth.

Quality Aspects –
Two basic phenomena are dealt with in the model: suspension and dissolution. For the former, two different modeling approaches were considered.

The first approach was based on the concept of critical scouring velocity. This critical velocity is computed as follows (Einstein, 1964; Environmental Protection Agency, 1971):

$$v_c = \frac{1.486}{n} R^{1/6} \left[k(S_s-1)d\right]^{1/2} \tag{8}$$

where v_c = critical scouring velocity, ft/sec

n = Manning's roughness coefficient

R = hydraulic radius, assumed herein to be equal to the depth of water, ft

k = Shield's coefficient

S_s = specific gravity of soil

d = diameter of soil particle, ft

If the flow velocity is less than v_c, no scouring takes place. If the opposite is true, scouring occurs and the uptake rate of a substance by the overland flow is set equal to a predetermined value, P_s. This formulation was abandoned due to the difficulty in estimating an upper limit to this uptake rate.

Instead the approach used involved the duBoys sediment load formula (Einstein, 1964):

$$q_s = \psi y S_b \left(y S_b - \frac{\tau_{cr}}{\gamma} \right) \tag{9}$$

where q_s = flux of sediment, lb/sec/ft of width

y = water depth, ft

ψ = a constant for a given bed composition

τ_0 = bed shear stress, lb/sq ft = $\gamma \, y S_b$

S_b = bed slope

τ_{cr} = critical shear stress, lb/ft^2

γ = unit weight of water, lb/ft^3

The computation of the phosphorous content of sediment loads is discussed in other portions of this work.

The formulation for the uptake rate of dissolved substances by the overland flow consists of a first-order reaction process, in which the rate decreases with time. It may be noted that the flux of substances at the downstream end of a catchment at any time is a result of prior events which occurred at upstream locations. For this reason, a time lag adjustment factor was used in the dissolved substances calculations.

Summary of Computer Program –
The main purpose of the kinematic wave program, known as KWAVE, is to compute runoff outflows from catchments into receiving elements. These receiving elements can be either large bodies of water, such as lakes and rivers, or simply surface depressions which are occasionally filled with water. The hydrologic data inputs to the program are the values of rainfall, evaporation and infiltration at the various time steps within the study period considered. As mentioned previously, to have manageable equations it is necessary to determine the time-average values of the above variables, which are then used instead of the raw data.

In addition to hydrological data, the program requires geometric information on each of the catchments, which are delineated in an approximately rectangular fashion. This information includes average length and width, slope and hydraulic friction factor (Manning's n). Also, a numbering system that links the subcatchments to the corresponding receiving bodies of water is provided.

The program has the capability of routing dissolved and suspended substances from the catchments into the receiving elements at every time step. For this purpose, the rates of dissolution and suspension must be computed from some basic data. These data include nutrient concentrations in fertilizers and their application rates, and effective diameter of soil particles.

Additional details on both the flow and quality computations in the kinematic wave model are provided in Appendix A. These discussions include sample calculations and descriptions of the various subroutines.

RECEIVING WATER MODEL

Quantity Aspects

The hydrodynamic response of any body of water is determined by two fundamental relationships: the equation of motion and the equation of continuity. The quantity program solves these two equations simultaneously in simulating the effects of hydrologic inputs to the receiving waters. In most practical situations, which involve time-varying hydrologic inputs (i.e., boundary conditions) and other complexities, an analytical solution of the above equations would become unwieldy. The approach taken is, therefore, to utilize numerical techniques in which the values of the variables are only considered at certain points in space and time.

An illustration of a simple hypothetical situation involving the receiving model is given in Figure 6. In this situation, the urban runoff from a city is discharged at a single location. Also, the river is divided into a number of reaches. The values of the hydraulic variables are then computed at the nodes dividing the various reaches. It may be noted that the input hydrograph must be provided in discrete, not continuous, form.

Hydraulic computations within the river or channel involve a stepwise iterative procedure. Given the hydraulic heads at two adjoining nodes, the hydraulic gradient and corresponding flow along the link is computed. As a result of this flow, the head at the downstream node is altered. The data required for each reach consist of surface area, width, length, depth and friction coefficient. At each node, the variables utilized are head and bottom elevations.

In many bodies of water, such as lakes and bays, the simple channel flow system depicted in Figure 6 would not adequately represent the actual situation. Instead, the flow in these water bodies is basically two-dimensional within a horizontal plane. Accordingly, the basic system of links (channels) and nodes (junctions) will constitute a grid covering the entire water body. An example of such a grid system is shown

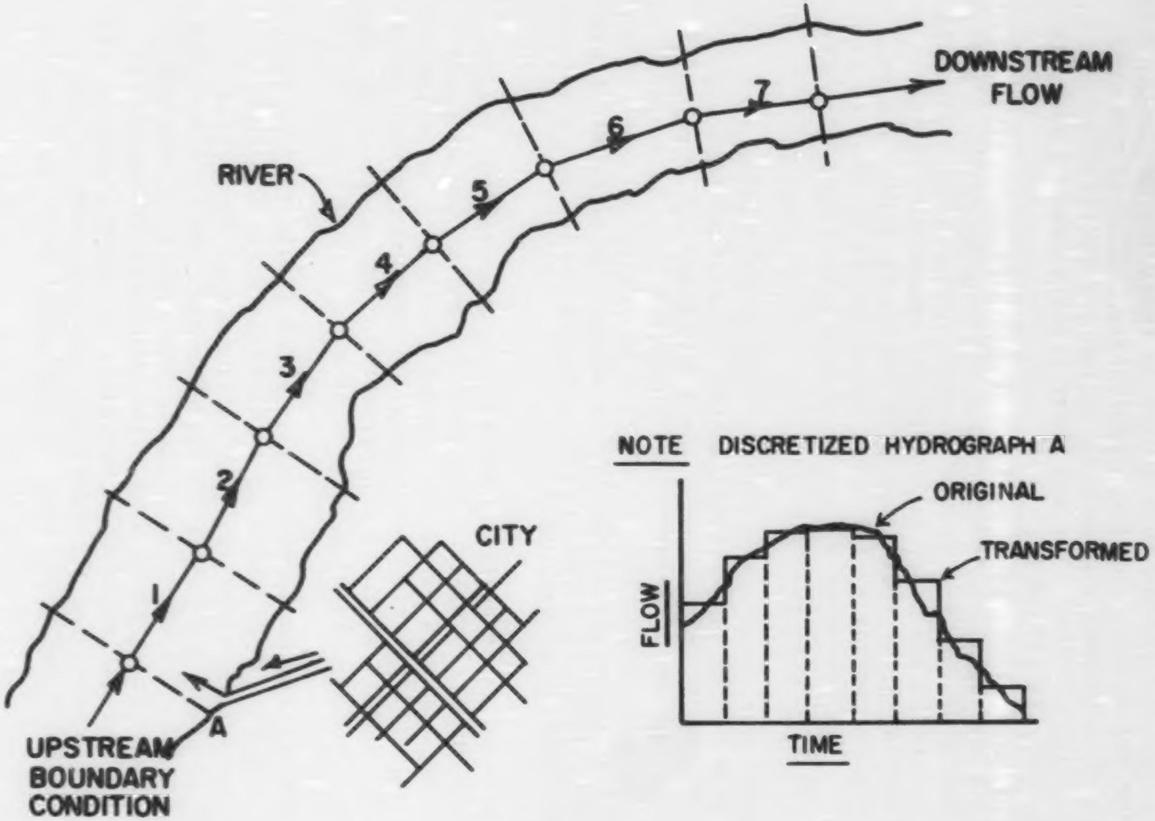

RIVER
DOWNSTREAM
FLOW
1
2
3
4
5
6
7
A
UPSTREAM
BOUNDARY
CONDITION
CITY
NOTE
DISCRETIZED HYDROGRAPH A
ORIGINAL
TRANSFORMED
FLOW
TIME

Figure 6. Illustration of a simple case involving the receiving water model.

in Figure 7 for the receiving portion of the Storm Water Management Model (Environmental Protection Agency, 1971) used in this study. In this case, the hydraulic computations follow an iterative procedure similar to that described above. The main complication added is the need to consider typically several channels in satisfying the continuity relationship at a given node. This and other factors tend to increase the computation time significantly.

Conceptually, both the location of the nodes and lengths of the links are arbitrary, and therefore the general pattern of the grid system can be irregular. However, from prior computational experience at the University of Florida, it has been concluded that efficiency is maximized as the areas delineated by the links approach the form of equilateral triangles. Selection of a fairly uniform link length throughout the system has also been found useful.

Within these guidelines, the node locations should be selected to lie as near as possible to the location of natural or man-made boundary conditions. In Figure 7, for instance, the node in the upper right hand corner of the bay was located in the vicinity of B, the runoff outfall point. Also, a tidal flow condition, basically of sinusoidal form, is provided at the mouth of the bay as shown. Other nodes should be placed in the vicinity of water quality sampling stations, if any, to facilitate calibration of the model.

In this study, several modifications were made to the original receiving model. In the original version, the outflow from a body of water was calculated using either a sinusoidal formula, valid in estuaries, or a weir equation, applicable to reservoirs. Another option was added herein; namely, to specify an outflow hydrograph of any shape. This option is applicable in the case of regulated canals.

Another improvement in the model consists of added flexibility in the types of inputs that can be provided to a receiving body. In the initial program package developed for the Environmental Protection Agency, the body of water could only receive the computed outflows from the urban runoff model. At the present time, the receiving body can also be provided flows computed by KWAVE, the rural runoff model. It may be noted that the location of the catchments in KWAVE should be made compatible with the location of the nodes near the periphery of the receiving body. These rural flows must be considered point sources for modeling purposes.

Finally, it was recognized that quite often small receiving bodies flow into larger ones. One example would be drainage canals flowing into lakes. For this reason, an interfacing methodology was developed for such a case.

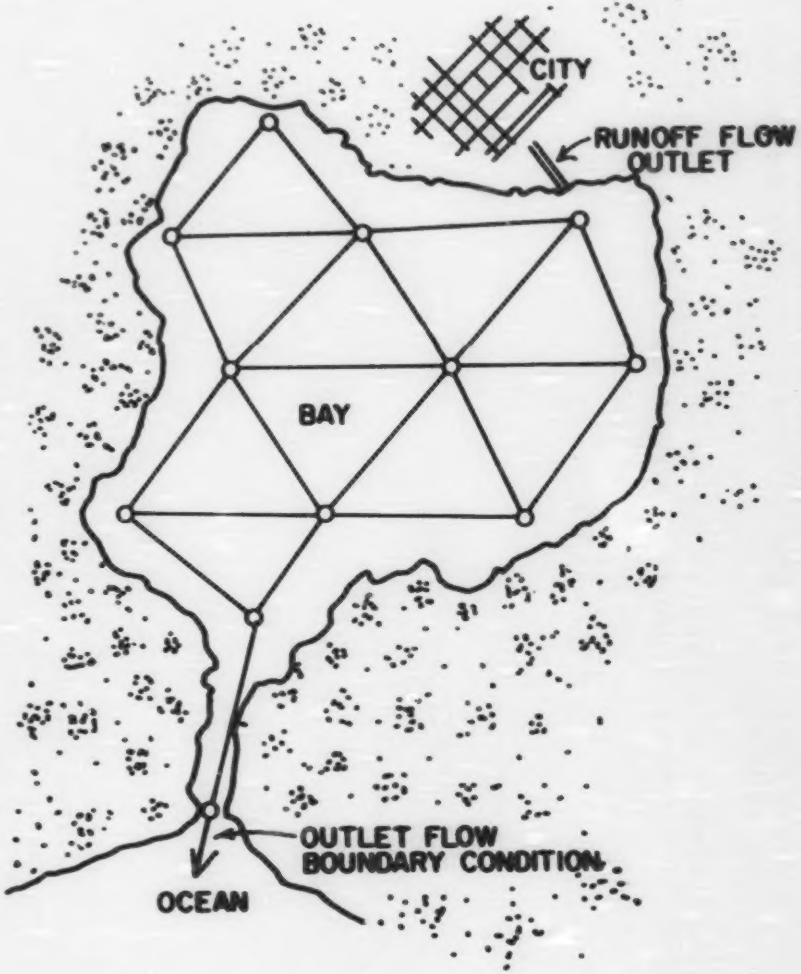

CITY
RUNOFF FLOW OUTLET
BAY
OUTLET FLOW BOUNDARY CONDITION
OCEAN

Figure 7. Typical receiving water model grid for two-dimensional flow.

Quality Aspects

The water quality subroutines of the receiving model consider both conservative and nonconservative pollutants. In routing these pollutants, the subroutines utilize the hydraulic data generated by the quantity program and the boundary fluxes. The quality processes formulated are advection, first-order decay and sources and/or sinks. The mechanism of diffusion was neglected. Nutrient cycling relationships from an ecosystem standpoint (Chen, 1969; DiToro, O'Connor and Thomann, 1970) were not included.

For a single branch system such as that shown in Figure 6, the basic finite-difference equation applied at a given junction or node is:

$$\frac{\Delta c_j}{\Delta t} = -v\frac{\Delta c_j}{\Delta x} - kc_j + S_j \tag{10}$$

where j = junction number

c = pollutant concentration, dimensionless

t = time, sec

v = velocity, ft/sec

x = distance, ft

k = decay constant, 1/sec

S = combined source/sink term, 1/sec

Thus the first term in the right-hand side of equation (10) represents advection, followed by decay and source/sink, respectively. At nodes where more than two links meet (see Figure 7), the advection term above is modified to include weighting factors corresponding to these links.

For additional informatin of the weighting procedure above, and on the sequential structure of the other calculations, the reader is again referred to the main source (Environmental Protection Agency, 1971). The quality program generates the concentrations of pollutants at all nodes for every time step.

SECTION V

UNSATURATED SOIL ZONE MODELS

INTRODUCTION

Following its entrance into the soil, water moves through it in a manner controlled by soil permeability, antecedent moisture conditions and other parameters. At this point, a semantic distinction can be made. According to McGauhey and Winneberger (1965), the term infiltration should refer exclusively to the vertical flow of water at the ground surface. On the other hand, the term percolation should be reserved to describe the flow at lower points within a soil profile.

The approach taken herein was to develop a formulation to predict flow and water quality conditions for a soil zone bounded by: (1) the ground surface at the top, and (2) the water table at the bottom. Such a zone and its boundaries are shown in Figure 8. The soil zone enclosed by these boundaries is denoted as the unsaturated zone because, in the general case, the void space in the soil is not totally occupied by water. Under some conditions, such as heavy rainfall, portions of the soil zone defined above may become saturated. Such a situation simply constitutes a special case of the general formulation. Another special case occurs in regions where groundwater discharge conditions and high evaporation rates are manifest in upward flows through the soil system.

It can be seen that the formulation for the unsaturated zone encompasses both infiltration and percolation as defined above. Although these two processes differ with respect to location, their mathematical representation is the same for practical purposes. For convenience, only the term infiltration is used in subsequent discussion, in a manner inclusive of both connotations above. Also, the term unsaturated flow is often utilized interchangeably with infiltration.

The state of the art in modeling this process varies according to whether its quantity or quality aspects are being considered. Since the quantity and quality processes are intimately related, the ultimate choice of model must constitute a compromise between the techniques available for the two aspects.

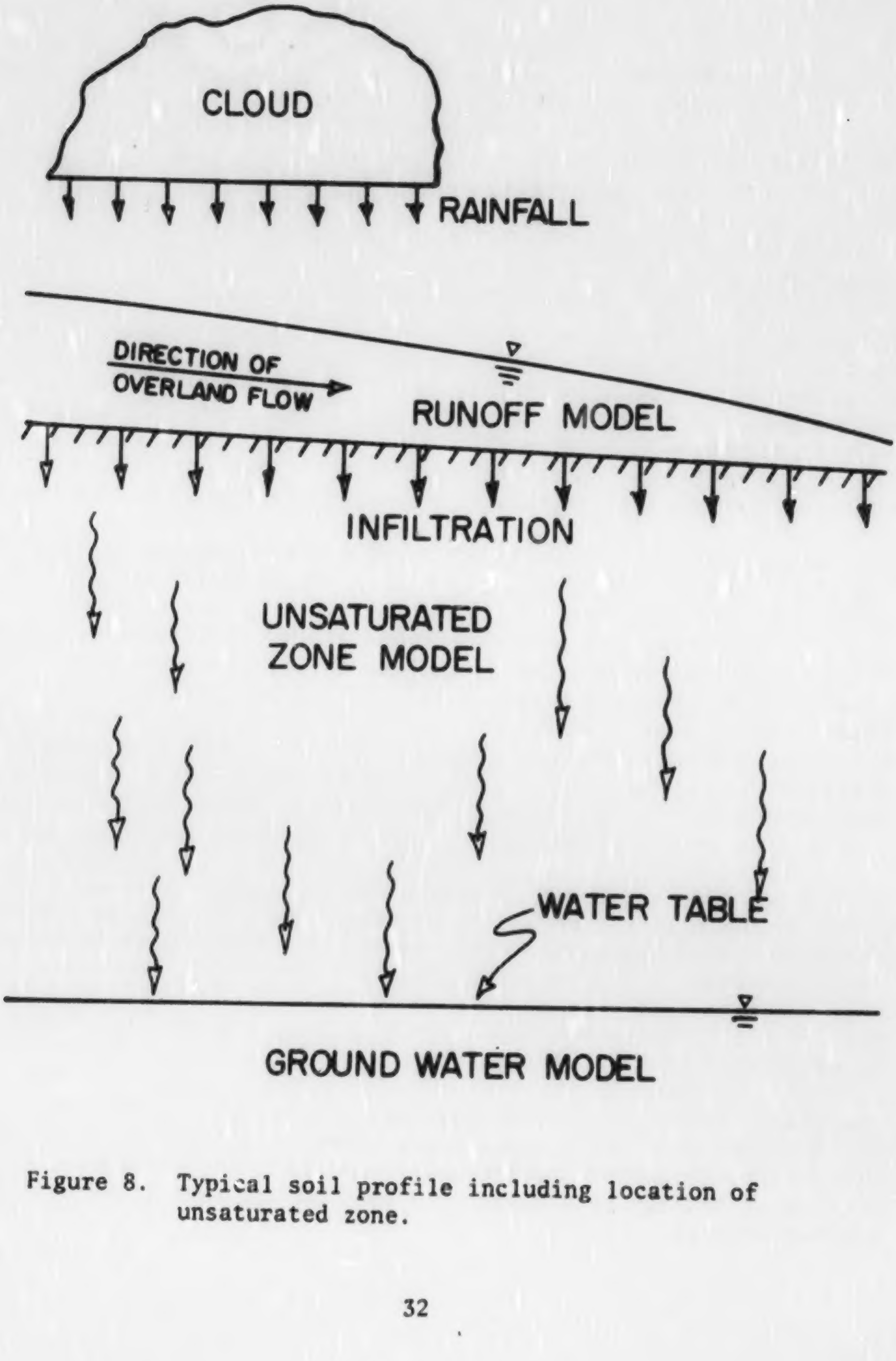

CLOUD
RAINFALL
DIRECTION OF OVERLAND FLOW
RUNOFF MODEL
INFILTRATION
UNSATURATED ZONE MODEL
WATER TABLE
GROUND WATER MODEL

Figure 8. Typical soil profile including location of unsaturated zone.

Investigations conducted on the flow aspects of infiltration are quite varied. One type of approach consists of empirical relationships derived from field work, such as soil percolation tests (McGauhey, Krone and Winneberger, 1966). Several researchers (Holtan, 1961) have developed formulations which now rely strongly on soil data collected by agencies such as the Soil Conservation Service. Other workers have obtained more theoretical relationships based essentially on Darcy's Law and the equation of conservation of mass (Klute, 1952).

In the area of water quality, work has been less extensive. Some detailed field studies have been conducted (Parizek *et al.*, 1967) in certain geographic regions. Also, some water quality formulations have been proposed to predict the concentrations of substances in the soil system (Tanji *et al.*, 1967). Most of these formulations, however, have been developed for substances other than nutrients.

STUDIES ON QUANTITY ASPECTS

Field Studies

Much of the hydraulic field work performed in soils has been with the intention of ascertaining the usefulness of a given soil as a wastewater treatment system. Sometimes the application method consists of intensive irrigation of crops. Thus, the maximum rate at which the wastewater can be applied to the soil is of great importance. Studies involving these aspects include those by McGaughey and Winneberger (1965), Frederick (1948), McGaughey, Krone and Winneberger (1966), and Winterer (1922).

A comprehensive study conducted at Pennsylvania State University (Parizek *et al.*, 1967) gives further insight into the importance of various geologic formations in site selection. It also provides some data on pollutant removals by the soil.

Quasi-Theoretical Approach

The formulations classified herein under this category are those whose basic premise is that the infiltration rate is inversely proportional to the degree of saturation of the soil. Various researchers have arrived at this relationship from more complex flow equations, and others have shown its applicability using soil tests. Gradually these quasi-theoretical formulations have been expanded to produce comprehensive watershed models.

In 1940, Horton defined the term infiltration capacity as the maximum rate at which soil can absorb incoming rain. He stated that this value decreases exponentially with time approaching a constant value asymptotically. In 1955, Philip reviewed the governing equations for infiltration, including Darcy's law and developed modified relationships. Later Philip (1957) conducted a study of the performance of the Horton and Kostiakov equations. As a result, he proposed the following infiltration equation:

$$i = st^{1/2} + A \tag{11}$$

where i = cumulative infiltration, in

s = sorptivity, in/hr$^{1/2}$

t = time, hr

A = infiltration parameter, in

Sorptivity is a measure of the capacity of the soil to absorb or desorb liquid by capillarity. The work of Holtan (1961) also related infiltration to the available soil porosity. The relationship proposed was

$$f - f_c = a\,F_p^n \tag{12}$$

where f = infiltration rate, in/hr

f_c = lower limit of infiltration rate, in/hr

a = a constant

F_p = potential volume of infiltration (a function of time, based on porosity and plant root structure)

n = a constant

In 1964, Holtan modified the usage of the above formulation and mentioned the testing of the improved method in various watersheds in the United States. In the same year, Overton developed an integrated form of the basic relationship given in equation (12), and compared it to the equations proposed by other researchers.

An early version of the watershed model developed by the Agricultural Research Service was applied to an area in Florida with good results (Sinha and Lindahl, 1970). Further efforts have resulted in a more versatile model, which utilizes soil and crop data collected routinely by agricultural agencies (Agricultural Research Service, 1971).

Since the Agricultural Research Service (ARS) watershed model was structured around infiltration relationships, other hydrologic flows such as overland flow are essentially computed indirectly by means of a budgeting process. The success of the ARS model, therefore, appears to depend largely on the proper calibration of its infiltration formulation. On the other hand, hydrologic models such as the Stanford Watershed Model (Crawford and Linsley, 1966) and the Kentucky Watershed Model (James, 1970) are calibrated primarily using gaged streamflows. In many areas where soils are highly permeable and subsurface flows are significant, as in the state of Florida, it would appear that the ARS model offers greater advantages.

Along with the increased efforts in the mathematical formulation of infiltration, field data have been collected to help verify and implement these models. Some examples of such studies are those by Free, Browning and Musgrave (1940), Stewart, Powell and Hammond (1963), Holtan *et al.*, and Choate and Harrison (1968).

Theoretical Approach

Much of the foundation work in the mathematics of flow through soils was completed in the 1950s. A 1952 paper by Klute presented the derivation of the flow governing equation using two basic relationships: the equation of conservation of mass and Darcy's law. In its original form, the governing equation contained two unknowns: moisture content and hydraulic potential. Klute pointed out the difficulties in solving this expression analytically and proposed a numerical solution instead.

Other papers similar to the above appeared in subsequent years. Freeze (1969), thoroughly delineated both the theory and the numerical methodology. Since this methodology was used in this study, it is discussed in some depth below.

Freeze began his formulation by defining the term hydraulic head as:

$$\phi = z + \psi \qquad (13)$$

where ϕ = hydraulic head, ft

z = elevation head, ft

ψ = pressure head, ft

The latter variable is commonly known as tension when its value is negative. In any system, the water flows in the direction of decreasing head, and the relationships controlling this flow are of interest.

The first relationship considered was Darcy's law, which for simplicity is written in the x-direction only:

$$v_x = -K(x,y,z,\psi)\,\frac{\partial\phi}{\partial x} \qquad (14)$$

where K denotes the hydraulic conductivity, ft/sec, which under saturated conditions equals the soil permeability.

The second basic relationship written was the equation of continuity, for the case of unsteady flow of a compressible fluid, namely

$$-\left[\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z}\right] + \frac{\partial}{\partial t}(\rho\theta)$$

where ρ = fluid density, slug/ft^3

θ = moisture content, %/100

v_x, v_y, and v_z = velocities in the three coordinate directions, ft/sec

After some simplifying assumptions, such as vertical flow only, homogeneity and incompressibility, equations (14) and (15) were combined to yield

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\phi}{\partial z}\right)\right] = \frac{\partial\theta}{\partial t} \qquad (16)$$

Some observations can be made about equation (16) above. Firstly, note that either ψ or ϕ may be eliminated using equation (13). Secondly, the difficulty presented by having two variables, say ϕ and θ, is apparent. The assumption is commonly made that ϕ and θ are related by means of a single-valued function, which can be determined experimentally for a given soil. However, in practice the relationship varies according to whether the soil is being wetted or dried, that is, a hysteresis effect exists. Secondly, the hydraulic conductivity is a function of pressure head (and also, therefore, of moisture content). Data on some or the relationships above are available for representative soils (Holtan et al., 1968).

The approach used in the formulation of an infiltration model is to first eliminate either ψ or θ from equation (16). Klute's method was to eliminate ψ and use a θ-based equation. On the other hand, Freeze eliminated θ and obtained the following equation

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z}+1\right)\right] = C(\psi)\,\frac{\partial\psi}{\partial t} \tag{17}$$

where $C(\psi)$ is defined as

$$C(\psi) = d\phi/d\psi \tag{18}$$

and thus can be evaluated from the moisture-pressure curve for a given soil.

In the numerical solution, a value of ψ is predicted at various locations in the porous medium using equation (17). A graphical representation of the situation for a one-dimensional, vertical flow is provided in Figure 9. The various nodes in the soil profile at which equation (17) is applied are shown. Also indicated are the flow boundary conditions at the upper and lower boundaries. Once the values of ψat the nodes have been computed, the corresponding flow velocities can be readily determined from Darcy's law.

Many other formulations have been developed based on the continuity equation and Darcy's law, (e.g., Fok and Hansen, 1966). Other authors have concentrated on specific portions of the general unsaturated flow problem. For instance, Rubin and Steinhardt (1963) directed their efforts toward the study of the upper boundary conditions in the soil profile specifically, ponding.

The approaches discussed so far have assumed the existence of a homogeneous soil. In 1962, Hanks and Bowers developed a numerical solution for flow through layered soils. Remson, Fungaroli and Hornberger followed in 1967 with another nonhomogeneous formulation. In 1970, Fok developed rules for modeling layered soil systems.

In 1970, Green et al. developed equations for two-phase flow (air and water) and considered the effect of hysteresis on soil moisture relationships. A paper by Freeze and Banner (1970) considered these problems of air entrapment and hysteresis.

STUDIES ON QUALITY ASPECTS

Background

As in the case of flow aspects, available water quality studies range from field and laboratory work to complex mathematical models. Some quality data collected in connection with wastewater recharge have been tabulated by Parizek et al., (1967) and McGauhey, Krone and Winneberger (1966). The balance of the major water quality research in the unsaturated zone may be broken down into three categories: (1) semiquantitative generalizations on the fate of various substances in unsaturated porous media, (2) developmental mathematical models and (3) applied mathematical models. The latter two types are based on the type of flow formulation depicted in Figure 9. The three categories listed are discussed below.

Fate of Substances

Considering nitrogen first, its chemistry in soils is strongly affected by biological activities. Nitrogen in organic form or in fertilizers can be converted to ammonia and then to the nitrate form. Also, nitrate may be reduced through nitrate to N_2 and then lost to the atmosphere by volatilization.

The degree of mobility of the various forms of N in soils varies considerably. Recent lysimeter studies (Bailey, 1968) have indicated that more than 99 percent of the soluble nitrogen in percolating water was in the form of nitrate, less than 1 percent was present as ammonia and only a trace of nitrite was detected. However, this breakdown can vary depending on the type of soil. In peat and muck soils, the ammonium form is present in large amounts in the percolating water. The explanation lies in the reducing power of these soils.

As discussed previously (equation 2), the ammonium ion and ammonia can coexist in water, and their relative amounts depend largely on pH. The ammonia molecule can be adsorbed by the soil, sometimes with the formation of NH_4^+. Also, volatilization of the ammonia occurs when its concentration is high and the ability of the soil to react with it is low. Volatilization is generally high from peat and muck soils (Bailey, 1968).

Numerous studies have also been conducted on the leachability of nitrogenous compounds. In 1939, Benson and Barnette directed their attention to the movement of fertilizers. Bates and Tisdale (1957) investigated the leachability of nitrate. Several experiments conducted by Bailey (1968) revealed that the leachability of organic N compounds was limited.

Turning now to phosphorous, the behavior of this substance differs markedly from that of mobile nitrate-nitrogen. Bailey (1968) has pointed out the large P-fixation capacities of some soils, and stated that most phosphorous compounds react strongly with the soil, with very little leaching into the subsurface water system.

Stanford, England and Taylor (1970) have compiled information on fertilizer use in the United States and its water quality effects.

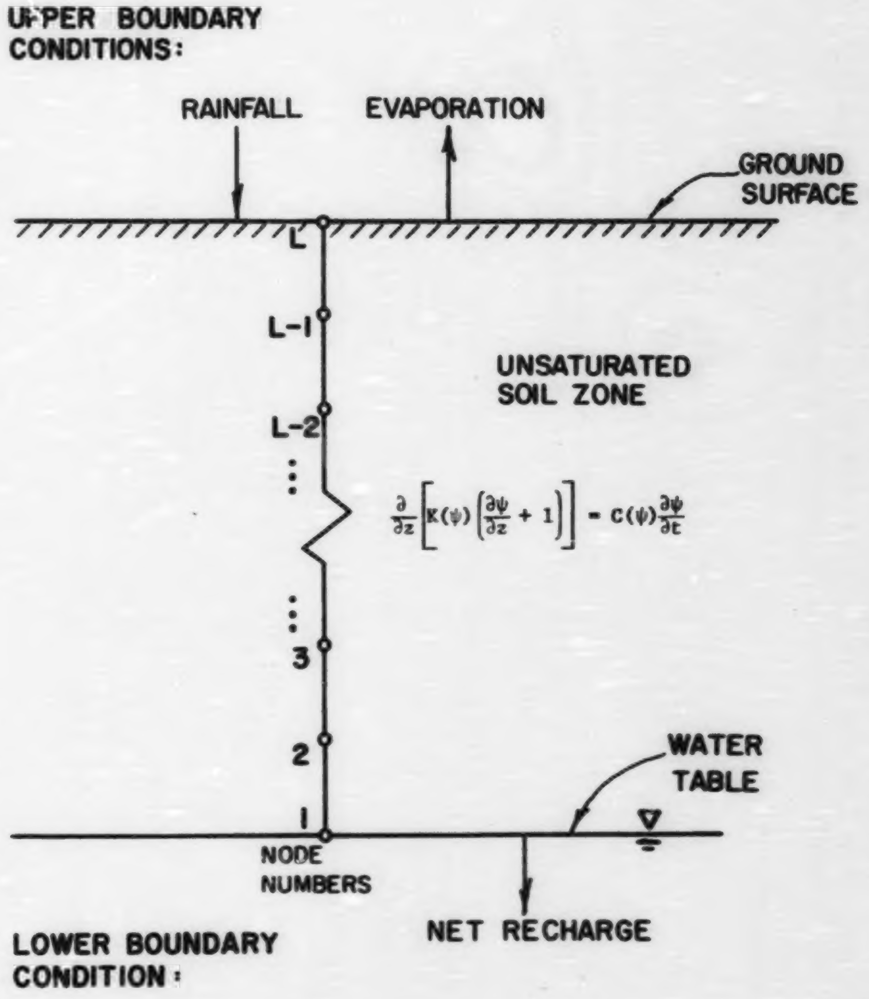

UPPER BOUNDARY
CONDITIONS:
RAINFALL
EVAPORATION
GROUND
SURFACE
L
L-1
L-2
3
2
1
UNSATURATED
SOIL ZONE
$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z}+1\right)\right] - C(\psi)\frac{\partial\psi}{\partial t}$
WATER
TABLE
NODE
NUMBERS
NET RECHARGE
LOWER BOUNDARY
CONDITION:

Figure 9. Graphical representation of vertical flow in the unsaturated zone.

The figures indicate that about 90 percent of the total N used was in the form of ammonia or ammonium salts. Just after application, therefore, the availability of highly leachable nitrate is not very significant. The ultimate presence of this ion in subsurface waters largely depends upon the degree of nitrification.

On the other hand, pollution from agricultural phosphorous occurs mainly as the erosion of soil material and its movement into surface bodies of water, and much less as transport in the unsaturated zone. It appeared, therefore, that modeling of phosphorous should be emphasized in runoff models and limited in unsaturated flow models.

Developmental Models

One of the earlier papers on water quality modeling in soils was written by Day and Forsythe (1957) who distinguished between dispersion and diffusion. They also reviewed Scheidegger's (1954) mathematical study on dispersion. Other papers that followed included those by Ashcroft *et al*., (1952), Dagan (1971), and Nakano and Murrman (1971). Bear (1972) presents a comprehensive review of dispersion and many other aspects of flow in porous media.

One significant conclusion can be drawn from a review of the above papers; namely, that in most cases, the effect of diffusion is very small relative to that of dispersion. The only exception to this rule would appear to be the case where the flow approaches stagnation.

Applied Models

The papers which fall under this classification are those in which the authors, rather than proposing a new approach, have instead attempted to adapt existing formulations to improve their predictive capacity. Some of these are: Miller, Biggar and Nielsen (1965), Dyer (1965), Warrick, Biggar and Nielsen (1971), Biggar, Nielsen and Tanji (1966), Tanji *et al*. (1967), and Oster and McNeal (1971).

DEVELOPMENT OF MATHEMATICAL MODELS

General Comments

The quantity and quality portions of any hydrologic model must be closely tied together. For this reason, the decisions on what quantity and quality formulations should be used could not be made independently. An overall model structure had to be developed which would accommodate both aspects.

Beginning with the flow or quantity models, it seemed that a choice could be made between two basic types: (1) watershed models such as that developed by the Agricultural Research Service (ARS) (1971) or (2) numerical solution of the unsaturated flow equation (Freeze, 1969). The first choice would offer several advantages; for instance, the fact that it has been verified at several locations in the United States, and its strong reliance on factors such as soil classification and crop type. However, the ARS model has one main drawback; namely, that it does not include water quality aspects.

The numerical solution approach also would offer some advantages, such as a more precise treatment of boundary conditions (refer to Figure 9) and the routing of water through the soil system. On the other hand, this method tends to overlook some problems encountered in practice. For example, many soils are not a continuous porous medium but rather contain appreciable discontinuities such as void spaces. For instance, it appears that much of the water that enters a cultivated soil moves down the walls of the plant roots. Furthermore, the soil moisture data necessary to utilize this approach, especially those on hydraulic conductivity, are often unavailable or erratic.

Turning to quality models, it seems that the most desirable method to route substances through soils is that based on solving the convection-dispersion equation numerically. Empirical and statistical relationships do not provide sufficient accuracy or understanding of the system. The numerical approach permits a detailed examination of processes which occur over short distances, and is flexible enough to allow the addition or elimination of certain terms, such as those involving sources and sinks.

For the above reasons, the decision was made to develop the water quality formulation around the numerical solution of the convection-dispersion equation. The remaining question was to determine what quantity formulation would be most desirable. A careful review of the ARS model indicated that the task of introducing a water quality submodel of the above type in it would be beyond the scope of this study.

Accordingly, the quantity model selected was that based on the numerical solution of the unsaturated flow equation. It is recognized that this approach is built upon idealized conditions, such as continuity of the porous medium. Therefore, several features were added to the basic formulation to remedy these deficiencies. These features include computation of water withdrawals by plants from the soil at different depths and also withdrawals through artificial drainage devices.

In both the quantity and quality aspects, the decision was reached to consider flow in the vertical direction only. The mathematics of a model involving more than one dimension would have been extremely complex. Also, in many basins the slopes of the water table are relatively gentle, indicating the lack of appreciable moisture gradients in the horizontal direction. In a region where this is not the case, the vertical flow condition can be approached by partitioning the region into subareas.

Additional details on the flow and quality models are given below.

Quantity Aspects

The flow formulation used herein is based primarily on Freeze's (1969) work. The principal function of this method is to predict the value of hydraulic pressure at different locations (nodes) in the soil profile. This is accomplished by solving the governing equation for unsaturated flow in finite-difference form. Once these pressure values have been determined, the corresponding velocities at every node can be computed using Darcy's law. These velocities are then stored for subsequent use in the quality calculations.

It is worthwhile to review the mechanics of the finite-difference approach. The governing equation being solved is equation (17), discussed previously, which for convenience is rewritten below

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right] = C(\psi)\frac{\partial\psi}{\partial t} + S \qquad (19)$$

in which, again, z = vertical coordinate, ft

t = time, hr

ψ = hydraulic pressure (head), ft

K = hydraulic conductivity, ft/hr

$C = \frac{d\theta}{d\psi}$ = slope of the moisture versus tension curve, 1/ft

S = sink term representing withdrawals of water by plants and/or artificial drainage devices, 1/hr

The sink term, S, constitutes an addition to the basic equation. It can be observed that derivatives are taken with respect to two variables: space and time. The basic approach in the numerical solution is therefore to compute the head at a given point in space and time in terms of head values at other locations in the space and time coordinates.

This approach is illustrated in Figure 10. Two time steps are shown, each having a set of boundary conditions and the same set of nodes. At any time step, the values of the top boundary variables can be obtained from hydrologic records. In turn, the value of the bottom variable, the net recharge, must be obtained by interfacing with the groundwater (saturated) flow model. For purposes of this discussion, it is assumed that the n-th time step on the right represents the present time. At this time, the values of head at each node must be computed. The heads at the previous time step have already been calculated.

Equation (19) can be rewritten in finite difference form (Freeze, 1969) and applied to the j-th node in the profile as follows:

$$
\begin{aligned}
C\left(\psi_j^{n-1/2}\right)\left[\frac{\psi_j^n - \psi_j^{n-1}}{\Delta t}\right] + S_j^n \\
= \frac{1}{\Delta z}\left\{K\left[\psi_{j+1/2}^{n-1/2}\right]\left[1 + \frac{1}{2\Delta z}\left(\psi_{j+1}^{n-1} + \psi_{j+1}^{n} - \psi_j^{n-1} - \psi_j^n\right)\right]\right\} \\
- \frac{1}{\Delta z}\left\{K\left[\psi_{j-1/2}^{n-1/2}\right]\left[1 + \frac{1}{2\Delta z}\left(\psi_j^{n-1} + \psi_j^{n} - \psi_{j-1}^{n-1} - \psi_{j-1}^n\right)\right]\right\} \qquad (20)
\end{aligned}
$$

where the subscripts associated with the head, ψ, designate the node and the corresponding superscripts indicate the time step. It can be observed that, in some cases, the value of ψ is computed at the midpoint locations between the grid nodes. In such cases, a simple averaging formula is used. For instance,

$$
\psi_j^{n-1/2} = \frac{1}{2}\left(\psi_j^{n-1} + \psi_j^n\right) \qquad (21)
$$

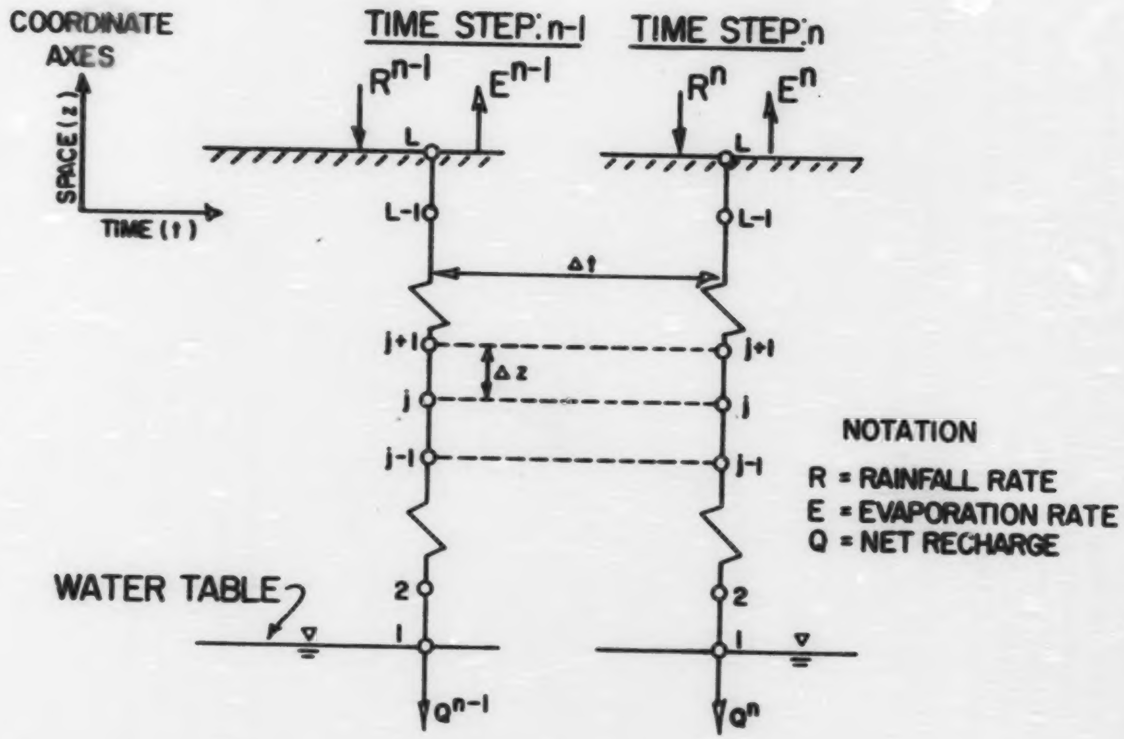

COORDINATE AXES
SPACE (z)
TIME (t)
TIME STEP: n-1
TIME STEP: n
R^{n-1}
E^{n-1}
R^n
E^n
L
L-1
Δt
j+1
Δz
j
j-1
2
1
WATER TABLE
Q^{n-1}
Q^n
NOTATION
R = RAINFALL RATE
E = EVAPORATION RATE
Q = NET RECHARGE

Figure 10. Illustration of the numerical solution for unsaturated flow.

Equation (20) relates the value of hydraulic head at an interior node, labeled j, to the values at its two adjoining nodes. An equation of the general form of (20) can be written for every node in the profile. However, the specific forms of the equation applied at the top and bottom notes are special cases. The type of relationship used in these cases consists of Darcy's law applied between the boundary node in question and its adjoining node, with the corresponding flow set equal to the corresponding known boundary condition flow.

For a profile containing L nodes (see Figure 10), there exists a system of L equations, with the same number of unknowns; namely, the head values at each node.

The system of equations can be written as:

$$
\begin{array}{lcccccc}
B_1\psi_1^n - A_1^n\psi_2^n & \cdots & 0 & \cdots & 0 & = D_1 & (1) \\
 & & \vdots & & \vdots & & \\
-C_2\psi_1^n + B_2^n\psi_2^n - A_2^n\,{}_3^n & \cdots & 0 & \cdots & 0 & = D_2 & (2) \\
\vdots & & \vdots & & \vdots & \vdots & \vdots \\
0 & -C_j^n\psi_{j-1}^n & + B_j^n\psi_j^n & - A_j^n\psi_{j+1}^n & 0 & = D_j & (j) \\
\vdots & & \vdots & & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & -C_L^n\psi_{L-1}^n & + B_L^n\psi_L^n & = D_L & (L)
\end{array}
\tag{22}
$$

The values of the coefficients A, B, C and D above can be computed from expressions which are derived in Appendix B. These derivations basically consist of regrouping of the terms found in equation (20). Expressions are also included for the coefficients used for the top and bottom nodes, which constitute special cases.

The left-hand side of system (22) above is commonly termed a tri-diagonal matrix. Due to this special form, the system is more easily solvable by an elimination procedure than by matrix inversion. A Gaussian elimination technique is used at each time step to obtain the desired set of values of head.

Prior to discussing the computer program for unsaturated flow, it is pertinent to mention other features of the formulation. One of these is the handling of a ponding condition at the surface. This situation arises when the net rainfall rate (rainfall minus evaporation) exceeds the saturated conductivity of the soil, and can continue for several time steps. As long as a ponding condition exists, the head at the top node is set equal to the ponding depth. This in effect constitutes the upper boundary condition, superseding the application of Darcy's law.

Other significant features, mentioned previously, are the computations of water uptake by plants and withdrawals through artificial drainage devices. These calculations, as applied to the Lake Apopka basin, are illustrated in Appendix E.

Some general sample calculations for the unsaturated zone flow model are provided in Appendix B. Also included is a description of the program subroutines.

Quality Aspects

At each time step, the quality formulation utilizes output from the flow program to route the movement of substances through the soil system. This output is basically in the form of moisture contents and flow velocities at each node.

In this investigation, it is assumed that the water quality processes that occur in the soil do not affect its hydraulic characteristics. This assumption is not always valid (McGauhey and Winneberger, 1965). However, it is felt that the assumption is justifiable in the context of the airms of this study, for various reasons. Firstly, the emphasis herein is on agricultural pollution in general, in which the phenomenon of clogging due to the action of microorganisms is much less significant than that in wastewater recharge. Secondly, there appears to be a lack of quantitative relationships linking these biological and hydraulic aspects.

A typical soil profile is shown in Figure 11. This profile is broken down into nodes. At the present time, assumed to be the n-th time step, the values of the moisture content and the velocity at each node are available from the unsaturated zone flow program. Also shown in this figure are boundary conditions affecting water quality.

The above boundary conditions can be classified as natural, such as rainfall and evaporation, or man-made, such as fertilizer input. The water quality implications of the phenomena in the first category have

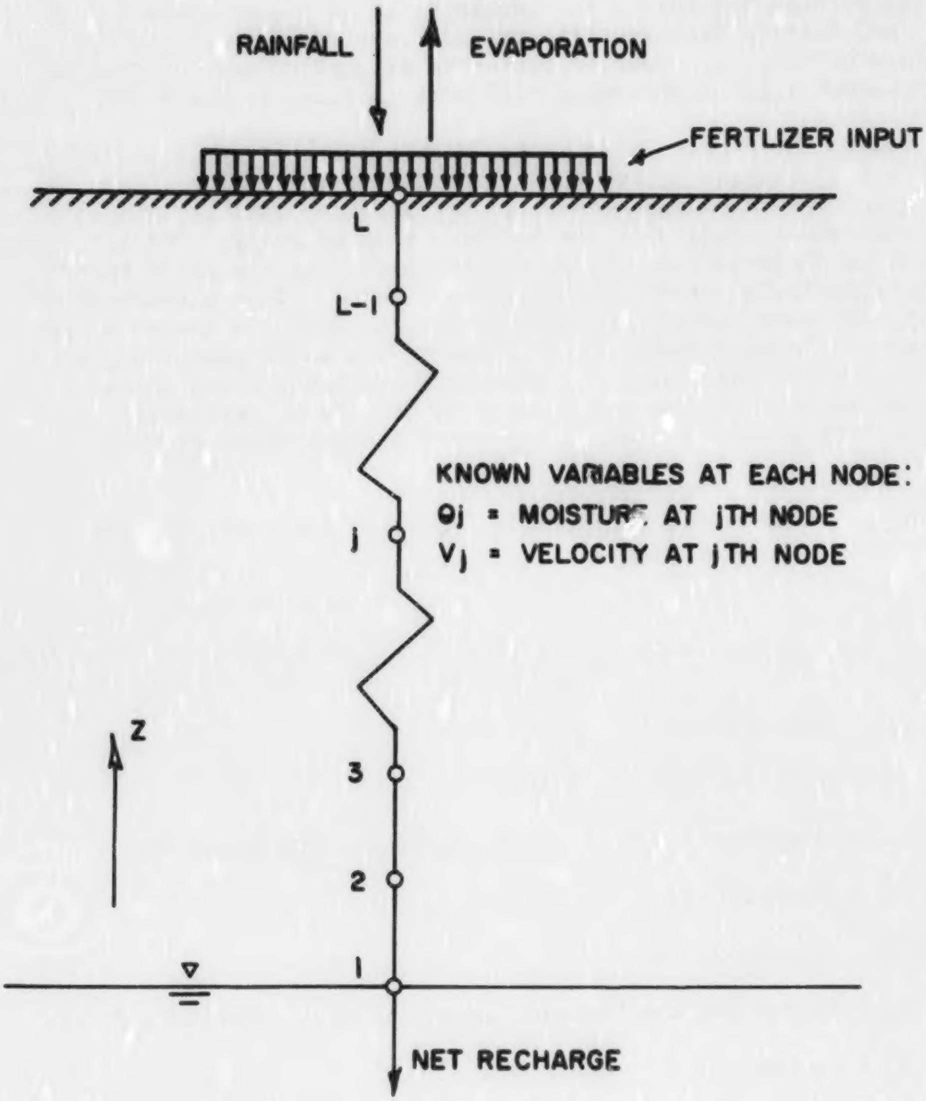

RAINFALL
EVAPORATION
FERTLIZER INPUT
L
L-1
KNOWN VARIABLES AT EACH NODE:
Θj = MOISTURE AT jTH NODE
Vj = VELOCITY AT jTH NODE
j
Z
3
2
1
NET RECHARGE

Figure 11. Schematic representation of soil system for water quality formulation.

been discussed previously. As might be recalled, no mathematical formulations were developed in this study for rainfall and evaporation.

The results obtained by Stanford, England and Taylor (1970) have been used herein to formulate simplifying assumptions about the travel of substances through the soil. For instance, it is assumed that all the nitrogen originating from fertilizers and traveling through the soil is in the form of nitrate. Another tentative assumption made is that all the phosphorous applied through fertilizers is fixed to the soil.

Turning now to the processes occurring within the soil profile itself, one consists of changes in concentrations due to changes in the moisture content with time and space. Another is advection; that is, the transport of substances along with the moving stream of water. The spreading phenomenon of dispersion is due to the tortuosity of the paths through which water particles travel in the porous medium. This phenomenon is generally much more significant than diffusion, which is caused by thermal motion of the molecules. In addition to the above processes, other physical, chemical and biological phenomena can occur which either add or withdraw substances from the flowing water. Terms designated as source/sink are generally used to represent a combination of these phenomena.

Accordingly, the governing differential equation for water quality in a soil profile can be written as:

$$\frac{\partial}{\partial t}(\theta c) = -v\frac{\partial c}{\partial z} + K_D(v)\frac{\partial^2 c}{\partial z^2} + S_o - S_i \qquad (23)$$

where t = time, hr

θ = moisture content, %/100

c = concentration of a given substance, dimensionless

v = velocity, ft

z = elevation, ft

$K_D(v)$ = dispersion coefficient (dependent upon velocity), ft^2/hr

S_o = source, 1/hr

S_i = sink, 1/hr

The left-hand side of equation (23) above can be expanded to yield the following expression:

$$c \frac{\partial \theta}{\partial t} + \theta \frac{\partial c}{\partial t} = -v \frac{\partial c}{\partial z} + K_D(v) \frac{\partial^2 c}{\partial z^2} + S_o - S_i \qquad (24)$$

Equation (24) above can, in turn, be written in finite difference form and applied to the j-th node in the soil profile at the n-th time step. The resulting expression, after some algebra, is

$$c_j^n \left(\frac{\theta_j^n - \theta_j^{n-1}}{\Delta t} \right) + \frac{\theta_j^n c_j^n}{\Delta t} - \frac{\theta_j^n c_j^{n-1}}{\Delta t} = \frac{v_j^n c_{j+1}^n}{2\Delta z} - \frac{v_j^n c_{j-1}^n}{2\Delta z} + \frac{K_D(v)_j^n c_{j+1}^n}{(\Delta z)^2}$$

$$- \frac{2K_D(v)_j^n c_j^n}{(\Delta z)^2} + \frac{K_D(v)_j^n c_{j-1}^n}{(\Delta z)^2} + S_{o_j}^n - S_{i_j}^n \qquad (25)$$

As in the unsaturated flow formulation, the subscripts and superscripts on the variables above denote the node and the time step, respectively. The derivation of equation (25) is given in Appendix B. Also included in this appendix are derivations for the expressions used at the top and bottom node, which constitute special cases.

The dispersion coefficients in equation (25) are indicated to be a function of velocity; a thorough discussion is found in Bear (1972). The actual formula used to compute the dispersion coefficient is based on experimental results given by Hoopes and Harleman (1965):

$$K_D = (\nu \alpha_3) \left(\frac{v (C_p)^{1/2}}{\nu} \right)^{\beta_3} \qquad (26)$$

where ν = kinematic viscosity of water (a function of temperature), cm^2/sec

α_3 = a constant

v = velocity, cm/sec

C_p = coefficient of intrinsic permeability, cm^2

β_3 = a constant

Additional discussion on equation (26), its units and the values of its constants is provided in Appendix B. This equation is representative of the data from which it was derived and is unlikely to be universally applicable.

Returning to equation (25), it may be noted that this expression basically relates the concentration of a substance at a given node to the concentrations at its two adjoining nodes. These three variables are the only unknowns in the equation. The values of all other variables are either known or can be computed from available data.

It follows then, that equation (25) can be rewritten in the form:

$$-(CC)_j^n c_{j-1}^n + (BC)_j^n c_j^n - (AC)_j^n c_{j+1}^n = (DC)_j^n \qquad (27)$$

The derivations of the expressions used to compute the coefficients AC_j^n, BC_j^n, CC_j^n and DC_j^n above are given in Appendix B for the case of an interior node and also for the cases of the top and bottom nodes. These derivations consist basically of regrouping of terms.

One water quality equation of the general form of (27) above can be written for every node in the soil profile. The resulting system of equations has the same structure as that shown in system of equations (22). Whereas the unknowns in (22) are the ψ's, the unknowns in the new system are the concentrations, computed at each time step in the program by Gaussian elimination.

Appendix B contains sample quality calculations and a description of program subroutines.

SECTION VI

GROUNDWATER MODELS

INTRODUCTION

The groundwater, or saturated, zone may be defined as the region of porous media in which the void spaces are totally occupied by water. The delineation of this region is illustrated in Figure 12 which represents a typical vertical cross-section in a basin. Shown therein are the ground surface, water table and two different geologic formations. According to the above definition, the water table constitutes the top boundary of the groundwater region. For purposes of analysis, it is desirable to define lateral and bottom boundaries for the system, shown as dotted lines. The location of these boundaries is facilitated by the existence of certain hydrogeologic features, (e.g. aquicludes). Somewhat arbitrary boundaries can also be used.

The movement of water within a given groundwater region is controlled by the flows occurring across its boundaries, such as recharge or discharge across the water table, and by hydraulic relationships within the region itself. More specifically, flow through saturated porous media is controlled by two basic relationships: Darcy's law and the equation of conservation of mass. The former states that the velocity at a certain point in the groundwater system is proportional to the hydraulic potential gradient at that location. The corresponding constant of proportionality, determined empirically for any given type of material, is known as the permeability or hydraulic conductivity. Discussions of this constant, its determination and the range of validity of Darcy's law are given by Todd (1967) and Bear (1972). These two relationships can be combined into a single expression, which can be used to predict flow velocities at different locations in the groundwater system. Data required to carry out this predictive process include flow boundary conditions and an initial hydraulic potential field.

As water moves through a groundwater system, it is subjected to physical, chemical and biological processes which affect the concentrations of its water quality constituents. Mathematically, some of these processes may be represented as terms in a water quality equation. Such processes

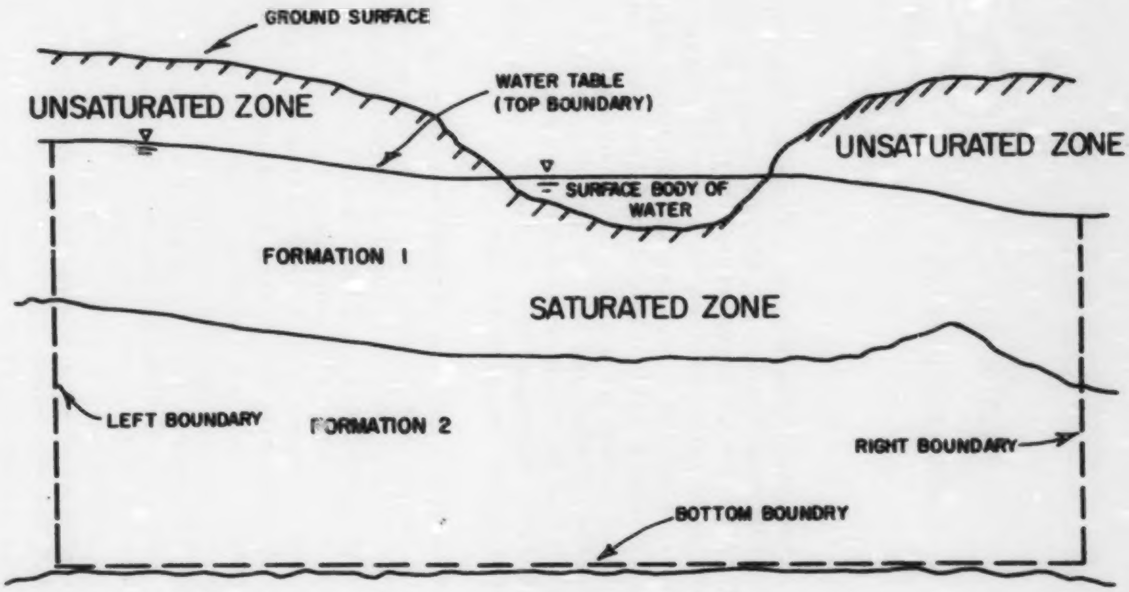

GROUND SURFACE
WATER TABLE
(TOP BOUNDARY)
UNSATURATED ZONE
UNSATURATED ZONE
SURFACE BODY OF
WATER
FORMATION 1
SATURATED ZONE
LEFT BOUNDARY
FORMATION 2
RIGHT BOUNDARY
BOTTOM BOUNDRY

Figure 12. Vertical cross-section of a groundwater system.

include advection, dispersion, diffusion, and sources and sinks. The source-sink rates, thought to be generally important, can only be roughly estimated from available data. An equation of the above type can be used to predict the concentrations of various substances at different locations within the groundwater system. Some terms in the equation, such as dispersion and advection, are a function of velocity.

LITERATURE REVIEW

Summary of Purposes

As in other hydrologic processes, a stepwise procedure is used herein in the modeling of groundwater. That is, at any time the flow or quantity computations are conducted first, followed by those involving water quality.

Quantity Aspects

Basic Theory—

Flow of groundwater is controlled by two relationships: Darcy's law and the conservation of mass equation (Todd, 1967). The former can be written in one-dimensional form as:

$$v_x = K \frac{d\phi}{dx} \tag{28}$$

where v_x = average flow velocity in the x-direction, ft/sec

K = permeability or hydraulic conductivity, ft/sec

ϕ = hydraulic head, ft

x = space coordinate, ft

The term $\frac{d\phi}{dx}$ above is known as the hydraulic gradient. Similar expressions can be written for the y and z space coordinates.

The second relationship, the conservation of mass equation, is also known as the equation of continuity. Assuming a steady-state situation (i.e., time-invariant boundary conditions) and an incompressible fluid, the continuity equation can be expressed as

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \tag{29}$$

Substitution of the expressions of Darcy's law (28), for each of the three coordinate directions, into equation (29) yields the steady-state form of Richard's equation (Freeze and Witherspoon, 1966), as follows:

$$\frac{\partial}{\partial x}\left(K(x,y,z)\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(x,y,z)\frac{\partial \phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(x,y,z)\frac{\partial \phi}{\partial z}\right) = 0 \qquad (30)$$

In the special case of a homogeneous medium, the permeability is constant and equation (30) may be simplified to

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = \nabla^2 \phi = 0 \qquad (31)$$

which is the Laplace equation. All the above equations, especially (28) and (29) serve as a basis for any steady-state groundwater formulation. The historical development of the major types of formulations is discussed below.

Hydraulics of Wells and Aquifers—

Much of the early work in ground water centered around radial flow into a pumping well. In 1906, Thiem investigated the steady-state aspects of well hydraulics. As a result, formulations for both confined and unconfined water-bearing formations, or aquifers, are available (Todd, 1967). In 1935, Theis developed the basic unsteady-state formulation for well flow. The main value of these well formulas, and their modified versions, lies in their use in pumping tests to determine aquifer permeabilities and other parameters.

In later years, other well formulations have been developed to allow less restrictive and more realistic assumptions on boundary conditions. An example of a realistic assumption is the existence of flow between a given aquifer and an adjacent semi-confining stratum (Hantush and Jacob, 1955).

Other improvements in well hydraulics formulations have permitted the analysis of complex boundary conditions and geometric configurations. According to Sternberg (1971), the handling of complicated geometric boundaries is best carried out by analog, rather than digital, computer techniques. Analog models have been used successfully to predict the response of aquifers to heavy pumpage in many areas, such as Las Vegas Valley (Domenico, Stephenson and Maxey, 1964). Details on the use of analog techniques are discussed in recent texts by Domenico (1972) and Bear (1972).

Although analog models allow great flexibility in the analysis of boundary conditions, the overall capability of digital models is stronger. As a consequence, numerous digital aquifer models are presently available. Examples are those developed by Trelease and Bittinger (1963), Engineering-Science (1971), Sechrist et al. (1971), Bredehoeft and Pinder (1970) and Neuman and Witherspoon (1970).

Groundwater flow systems—
Another major type of research effort in ground water has been the development of the flow systems approach. In contrast to the above emphasis on radial flow occurring in a certain portion of a ground water basin, this approach is more concerned with the basin as a whole and with the understanding of general flow patterns. Thus, the widespread use of terms such as aquifer versus aquiclude (also, confined and unconfined), which tend to denote absolutes, is replaced in the systems approach by consideration of relative values of permeability at various locations. All geologic formations are assumed to have some permeability, however small it might be.

Also, the flow systems method places great weight on the delineation of recharge and discharge areas, and the relation of these features to the overall movement of water in the saturated zone. It follows that for a study of basin-wide water quality with various sources of pollutants, the systems approach appears to offer great flexibility and promise. Some major developments in this approach are discussed below.

Much of the fundamental work in groundwater flow systems was carried out by Hubbert in 1940. In 1962 and 1963, Toth applied the principles proposed by Hubbert to the analysis of groundwater motion in small basins. Further application of flow theory to geology was conducted by Maxey and Hackett (1963).

In 1966, Freeze and Witherspoon utilized the groundwater flow systems approach in developing a two-dimensional steady-state model. In a subsequent paper, Freeze and Witherspoon (1967) discussed geohydrologic features such as water table configuration and the occurrence of recharge and discharge, and their formulation as boundary conditions in the mathematical model. In their steady-state formulation, these boundary conditions are assumed to be time-invariant. Also contained in this paper are useful rules of thumb which permit the deduction of general flow patterns in a basin from geologic and geographic information.

The two-dimensional model developed by Freeze and Witherspoon (1966) can be applied to selected vertical cross-sections of the type shown in Figure 12. The sufficient condition for the validity of the two-dimensional approach therein is that no significant flow actually occurs in the direction incidental to the plane of the section. Accordingly, the cross-sections to be used in the analysis of a basin should be carefully chosen using potentiometric data which indicate flow paths. This process is illustrated in Section VIII.

Assuming that the two-dimensional assumption is valid for the selected cross-section, the first step in using the model consists of superimposing a grid system, as shown in Figure 13. The main function of the formulation is to predict the value of hydraulic head at each node in the system. To achieve this objective, Freeze and Witherspoon utilize a finite-difference form of equation (30) as the basis of an iterative approach. The final values of head obtained at each node are then used to compute the corresponding flow velocities by means of Darcy's law (28).

In an attempt to increase the generality of his flow systems approach, Freeze proposed in 1971 a three-dimensional, unsteady-state formulation. At the present time, complete verification results of this numerical model are not available. Many of the basic numerical techniques used by the above and other workers in subsurface hydrology have been discussed in a text by Remson, Hornberger and Molz (1971).

Estimation of Hydrogeologic Parameters—

The successful verification of any groundwater model depends heavily upon the estimation of hydrogeologic parameters such as permeability. A general discussion on parameter estimation methodologies in hydrology has been presented by Jackson and Aron (1971).

The available works on parameter estimation in groundwater may be classified according to whether they are primarily applicable to aquifer pumpage problems or to general flow systems. In the former category, papers are available by Haimes, Perrine and Wismer (1968), Yeh and Tauxe (1971) and Kleinecke (1971).

Parameter estimation in general flow systems involves great difficulty. This is due to the large number of different geologic formations and the areal variability of flow boundary conditions such as recharge and discharge. Some of the problems have been recognized by Nelson (1960), Freeze and Witherspoon (1967), and Simpson, Kisiel and Duckstein (1971).

Selection of Flow Model—

A review of the main goal of this particular study, namely the development of a basin-wide relationship, indicated that the most desirable type of flow model was that based on the flow systems concept. Also, the emphasis of this approach on recharge and discharge relationships makes it well-suited to analyze agricultural effects. Accordingly, the two-dimensional, steady-state formulation by Freeze and Witherspoon (1966) was selected.

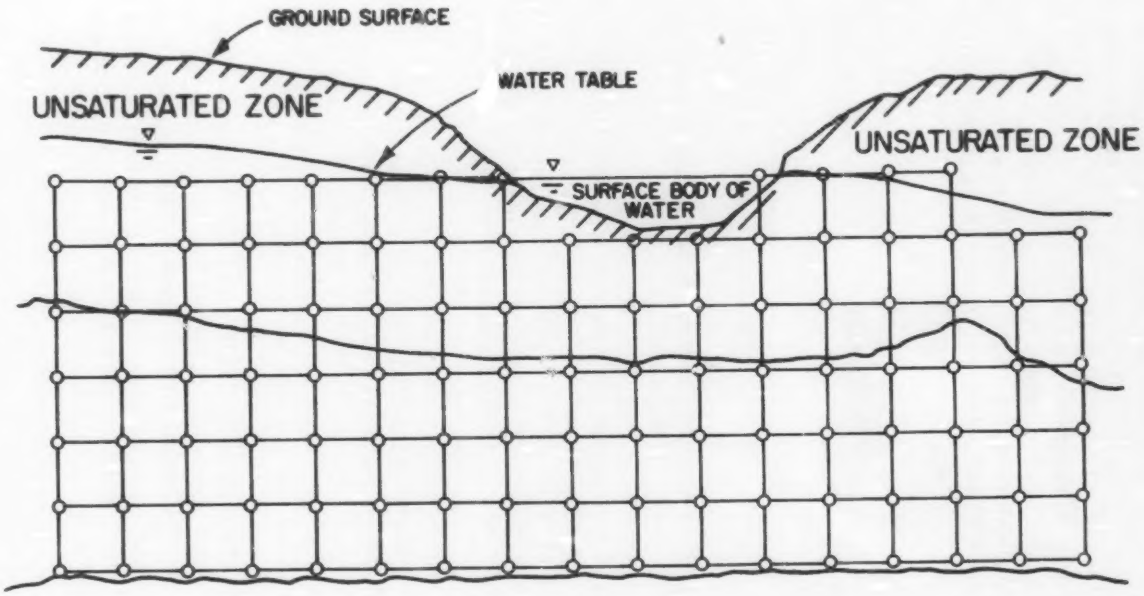

GROUND SURFACE
WATER TABLE
UNSATURATED ZONE
SURFACE BODY OF WATER
UNSATURATED ZONE

Figure 13. Grid structure superimposed on a groundwater cross-section.

Some consideration was given to using the three-dimensional, unsteady-state model developed by Freeze (1971). However, the computational cost to be brought about by an additional dimension was thought to be unwarranted. Also, in many basins adequate potentiometric data are available, allowing a fairly accurate delineation of cross-sections for analysis. Finally, in agricultural basins, boundary conditions (such as water table elevations) do not vary rapidly but rather undergo long-range and seasonal changes (Orsborn, 1966). Therefore, the use of a transient formulation can be effectively substituted by that of a steady-state approach at a series of relatively long time intervals.

The two-dimensional, steady-state model used allows the computation of the velocity field and is thus compatible with most of the available water quality formulations.

Quality Aspects

Background—

The concentration of various substances in ground water is controlled by physical, chemical and biological actions.

The physical category includes dispersion and diffusion. These two phenomena involve spreading and mixing of substances, but their causal mechanisms are different. Dispersion is due to velocity fluctuations resulting from the tortuosity of the flow paths in the medium. Diffusion, on the other hand, is associated with random thermal motion of molecules.

The significance of chemical reactions in ground water varies with the type of medium and other natural conditions. In clay soils, the predominant reactions would occur in the form of ion exchange. Limestones tend to dissolve in water, producing high hardness values. All these reactions occur until equilibrium is reached.

Biological actions are the most difficult to quantify. However, it may be speculated that these activities are less complex in the ground-water region than in the unsaturated zone. The reason would lie in the filtering of organisms and organic matter by the soil, sometimes within the first few feet of travel. In any case, data on the impact of biological activity are very scarce.

Dispersion and Diffusion—

According to Day and Forsythe (1957), diffusion of ions is a process independent of hydrodynamic dispersion. Work on both of these phenomena has been carried out by Scheidegger (1954), Bear (1961), Scheidegger (1961), Bachmat and Bear (1964), and Brutsaert (1968). A comprehensive review is found in Bear (1972).

Scheidegger's 1961 paper further developed the mathematics of dispersion. Theoretical arguments up to that time indicated that there were two possible expressions relating the factor of dispersion to the velocity:

$$D = av \qquad (32)$$

or,

$$D = av^2 \qquad (33)$$

where D = dispersion factor

a = geometrical dispersivity

v = velocity.

After reviewing experimental results, Scheidegger concluded that (32) was the correct expression.

Turning to the relative importance of dispersion versus diffusion, it may be recalled that the latter has been usually neglected in calculations. In 1967, Hoopes and Harleman tested the validity of the above simplification by means of a tracer study. They found that the omission of diffusion terms from the general dispersion-diffusion expressions did not significantly increase the discrepancy between calculated and observed concentrations. This result was obtained for both the longitudinal and transverse directions.

As a part of the same investigations, Hoopes and Harleman (1965) developed expressions for the dispersion coefficient. One equation proposed was:

$$K_D = (\nu\alpha_3)\left(\frac{v(C_p)^{1/2}}{\nu}\right)^{\beta_3} \qquad (34)$$

where K_D = dispersion coefficient, cm^2/sec

ν = kinematic viscosity of water, cm^2/sec

C_p = coefficient of intrinsic permeability, cm^2

v = flow velocity, cm/sec

α_3, β_3 = constants

The above expression (the range of validity of which, as mentioned earlier, is uncertain) is also used herein for dispersion calculations in the unsaturated zone. In that regime, the intrinsic permeability is derived from the variable hydraulic conductivity.

Source-sink Factors—
The fact that various reactions occur between the moving water and the geologic formations has been recognized for many years as shown by the work of Kaufman *et al.* (1961), Champlin and Eicholz (1968), Scalf *et al.* (1969), and Stanford, England and Taylor (1970).

Consideration of the available literature on source-sink interactions reveals the lack of a unifying mathematical formulation. However, the approach proposed by Back and Hanshaw (1970) appears promising. These researchers have pointed out that perhaps the hydraulic potential energy should not be considered as a separate entity, but rather should be integrated with other chemical and thermal energy factors. The pursuit of this approach, while worthwhile, would extend beyond the scope of this particular study.

Selection of Quality Model—
The selection of the water quality formulation involved decisions on the various processes to be included in the governing equation. In view of the available data on the relative importance of dispersion and diffusion, the latter phenomenon was neglected. Also, source-sink terms were not considered due to lack of data. However, the type of advection-dispersion model chosen below is one in which source-sink terms could be incorporated with relative ease. Nitrate is the only substance being routed at present.

An extensive survey of two-dimensional advection-dispersion formulations has been conducted by Bedient (1972) as part of an estuarine water quality simulation study. These numerical procedures utilize a previously computed set of velocity components at the grid nodes, along with initial and boundary conditions, to calculate the pollutant concentrations at all the nodes. Bedient's work was based on a model developed by Shamir and Harleman (1966), which is effective in reducing numerical error.

In its original form the Shamir and Harleman model was designed to solve the basic transport equation in an orthogonal curvilinear coordinate system. It was subsequently modified by Bedient for applicability to any two-dimensional coordinate system, as follows:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = D_x\frac{\partial^2 c}{\partial x^2} + D_y\frac{\partial^2 c}{\partial y^2} \qquad (35)$$

where c = concentration of substance, dimensionless

u, v = horizontal and vertical velocities, respectively, ft/sec

t = time, sec

x, y = coordinate directions, ft

D_x, D_y = dispersion coefficients in the x and y directions, respectively, ft^2/sec.

QUANTITY MODEL

Basically, the approach used herein (Freeze and Witherspoon, 1966) consists of applying a finite-difference form of Richard's equation (30), in only two dimensions, to every node in a grid system such as that shown in Figure 13. The values of hydraulic head at each node are predicted using the above finite-difference equations as part of an iterative procedure. Subsequently, the two components of velocity at the nodes are computed from Darcy's law.

For discussion purposes, it is worthwhile to select a small section of a large grid system, such as that shown in Figure 13, for detailed analysis. This isolation process is illustrated in Figure 14. Indicated in the upper left hand portion of the figure is an arbitrary section of a grid system. Also shown is information on the coordinate axes and the horizontal and vertical spacings.

The interior node having coordinates (I, J), and its four adjoining nodes, are shown in more detail in the right-hand side of Figure 14. The finite difference solution procedure to predict the head at the central node utilizes the heads at its adjoining nodes and both the horizontal and vertical permeabilities at all five nodes. In addition to the above, permeabilities and heads are evaluated at locations midway between the nodes.

In two dimensions, the original form of the governing equation (30) reduces to

$$\frac{\partial}{\partial x}\left[K(x,z)\frac{\partial\phi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(x,z)\frac{\partial\phi}{\partial z}\right] = 0 \qquad (36)$$

The finite-difference form of the first term in the above equation, applied to node (I, J) can be written as:

$$\frac{\partial}{\partial x}\left[K(x,z)\frac{\partial\phi}{\partial x}\right] = \frac{\left[K\frac{\partial\phi(I-1/2,J)}{\partial x}\right] - \left[K\frac{\partial\phi(I+1/2,J)}{\partial x}\right]}{\Delta x} \tag{37}$$

A counterpart expression can be developed for the second term in (36) above. Following the expansion of midpoint terms and regrouping in equation (37) and its counterpart, the following expression is obtained (Freeze and Witherspoon, 1966):

$$\phi(I,J) = \frac{\left[K_H(I-1,J)\phi(I-1,J) + K_H(I,J)\phi(I+1,J) + \alpha K_V(I,J-1)\phi(I,J-1) + \alpha K_V(I,J)\phi(I,J+1)\right]}{K_H(I-1,J)+K_H(I,J)+\alpha K_V(I,J-1)+\alpha K_V(I,J)} \tag{38}$$

where K_H, K_V = horizontal and vertical permeability, respectively

α = $\left(\frac{\Delta x}{\Delta z}\right)^2$

Equation (38) is applicable only to interior nodes, that is, those having four adjacent nodes. Special forms of this expression have been developed for boundary nodes, which have fewer adjacent nodes. Also, the heads at certain locations, such as the water table, are known and therefore no computations are required for these nodes. Finally, flow boundary conditions may be defined by setting head values in the vicinity of the physical boundaries. A node classification system has been devised to distinguish between these various cases.

The prediction of heads throughout the grid system consists of a trial and error process, involving several iterations. To promote convergence, a relaxation factor is applied to each value of head after its computation, as follows:

$$\phi(I,J)^{(n)}_{(c)} = w\phi(I,J)^{(n)}_{(p)} + (1-w)\phi(I,J)^{(n-1)}_{(c)} \tag{39}$$

in which w denotes the relaxation factor. The superscripts, n or n-1, indicate the iteration step. The subscripts c and p are abbreviations for the terms corrected and predicted, respectively.

After a desired tolerance in the predicted values of head has been achieved, it is possible to compute the horizontal and vertical components of velocity at the various nodes. For this purpose, Darcy's law is applied in finite-difference form in the s- and z-directions.

Sample calculations for the groundwater flow model and a discussion of its subroutines are provided in Appendix C.

QUALITY MODEL

The function of the quality formulation is to predict the concentrations of a given pollutant at all nodes in a grid system such as that shown in Figure 13. For this purpose, it utilizes the velocity components determined by the flow model along with initial and boundary conditions for the pollutant in question. Specifically, the quality model solves the advection-dispersion equation (35) using various numerical techniques. It may be noted that the y-coordinate in equation (35) corresponds to the vertical z-coordinate used in the flow model, as shown in Figure 14. Since the solution procedure for the quality model has been discussed extensively by Bedient (1972), only a brief explanation thereof is given below.

The original Shamir and Harleman (1966) formulation, adapted by Bedient to cartesian coordinates, combined the techniques of several investigators to minimize numerical error. One of these techniques is the application of weighting factors to the various time and space finite difference terms in the governing equation (35). The optimal values of these weights were determined by Stone and Brian (1963) using Fourier analysis.

Another feature incorporated into the formulation is the alternating direction implicit (ADI) scheme proposed by Peaceman and Rachford (1955). At any given time, the ADI procedure first solves a form of equation (35) in the horizontal direction, and subsequently solves a similar form in the vertical direction. The solutions obtained in the two above steps consist of intermediate, or temporary, concentration values at each node in the grid system.

The ADI method can be discussed further by referring to the right-hand portion of Figure 14. Considering the horizontal direction first, the following generalized finite-difference equation can be written for a given node with coordinates (i,j) after rearranging terms in equation (35):

$$-C_{i,j}c^*_{i-1,j} + B_{i,j}c^*_{i,j} - A_{i,j}c^*_{i+1,j} = D_{i,j} \qquad (40)$$

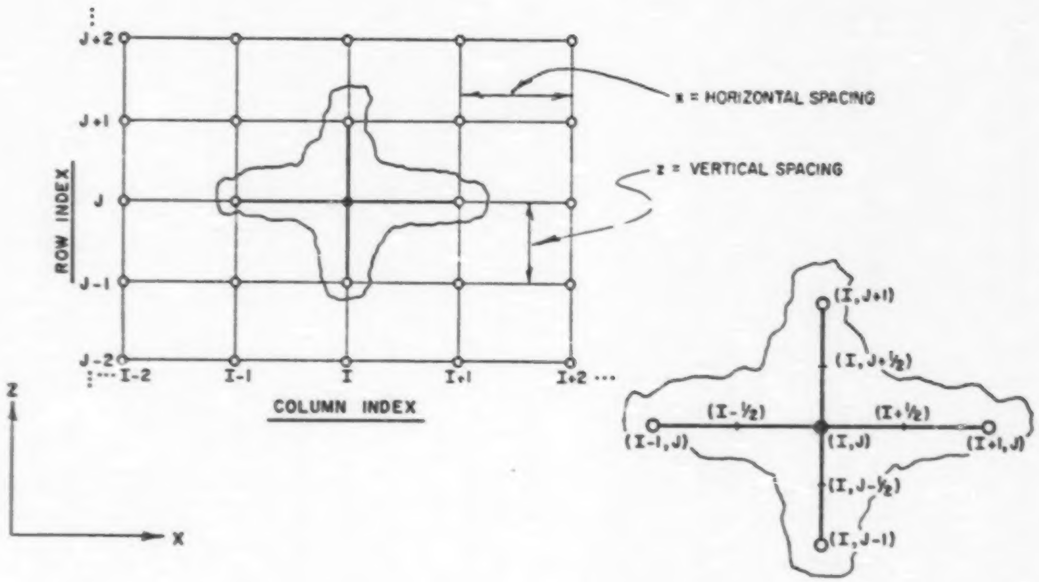

J+2
J+1
J
J-1
J-2
ROW INDEX
I-2
I-1
I
I+1
I+2 ...
COLUMN INDEX
x = HORIZONTAL SPACING
z = VERTICAL SPACING
z
x
(I,J+1)
(I,J+½)
(I-½)
(I+½)
(I-1,J)
(I,J)
(I+1,J)
(I,J-½)
(I,J-1)

Figure 14. Details of a groundwater grid system.

where c^* = intermediate concentration of pollutant at a given node

A, B, C = left-hand side coefficients (constants)

D = right-hand side constant

Since equation (40) can be written for each node, a system of such equations is required to describe the entire grid structure. The resulting system of equationsis of tri-diagonal form, and the values of concentration are obtained using the elimination procedure algorithm developed by Thomas (1949). It may be recalled that this solution scheme is analogous to that used in the unsaturated zone models.

In the vertical direction, an equation similar to (40) above can be written for the same node, namely:

$$-C'_{i,j}c^{**}_{i,j-1} + B'_{i,j}c^{**}_{i,j} - A'_{i,j}c^{**}_{i,j+1} = D'_{i,j} \qquad (41)$$

where c^{**} = second intermediate pollutant concentration

A', B', C' = second set of left-hand side coefficients

D' = second right-hand side constant

Likewise, the system of equations involving all nodes is solved by means of the Thomas algorithm.

After the two basic steps in the ADI procedure have been completed, the quality formulation computes the final concentrations throughout the system using an explicit scheme. The intermediate values of concentration, determined above, are used in these computations.

Finally, it is pertinent to mention briefly the types of boundary conditions used in the formulation, in order of increasing complexity:

1. A value of concentration, c, is specified at a given boundary node.
2. The concentration gradient is set equal to zero at a given boundary. This is known as the reflection boundary condition, and it implies that no dispersion occurs across the boundary.
3. The concentration gradients on both sides of the boundary are set equal.
4. The difference between the mass flux entering a control volume in the vicinity of the boundary and the flux leaving it is equated to the change in storage.

The usage of some of these boundary conditions is illustrated in Section VIII.

SECTION VII

INTERFACING OF MODELS

INTRODUCTION

To predict flow and water quality conditions on a basin-wide basis, it is necessary to link together the various computer models discussed previously. Figure 15 consists of a vertical cross section of a typical basin which indicates the formulations applied to different portions of the system.

The interfacing methodology consists of the exchange of flow and quality information between the different models shown in Figure 15. In developing this methodology, the trade-off between two factors must be considered: (1) computational convenience and (2) conformity with the natural system. Due to size limitations in computer storage facilities, it is generally infeasible to carry out the computations for all the models on an integrated basis. Thus, it becomes necessary to establish a sequence in which the various programs should be run. Ideally, this order would follow the paths of water particles as they move within the system. However, since most basin-wide flow patterns are multidirectional, a compromise sequential system must be developed.

The discussions below include further consideration of stepwise computations and their corresponding data linkages. Information on the types of data used in these transfers is provided. Also included is a discussion of programming and usage factors.

GENERAL COMMENTS ON SEQUENTIAL APPROACH

At present, the only feasible methodology is to run the various programs in a stepwise fashion. The selection of this sequential procedure should be made in a manner that minimizes distortion of the natural processes.

Prior to developing a stepwise approach for a given study area, it is advisable to run the individual models under a variety of boundary conditions. Since these boundary conditions represent the interactions

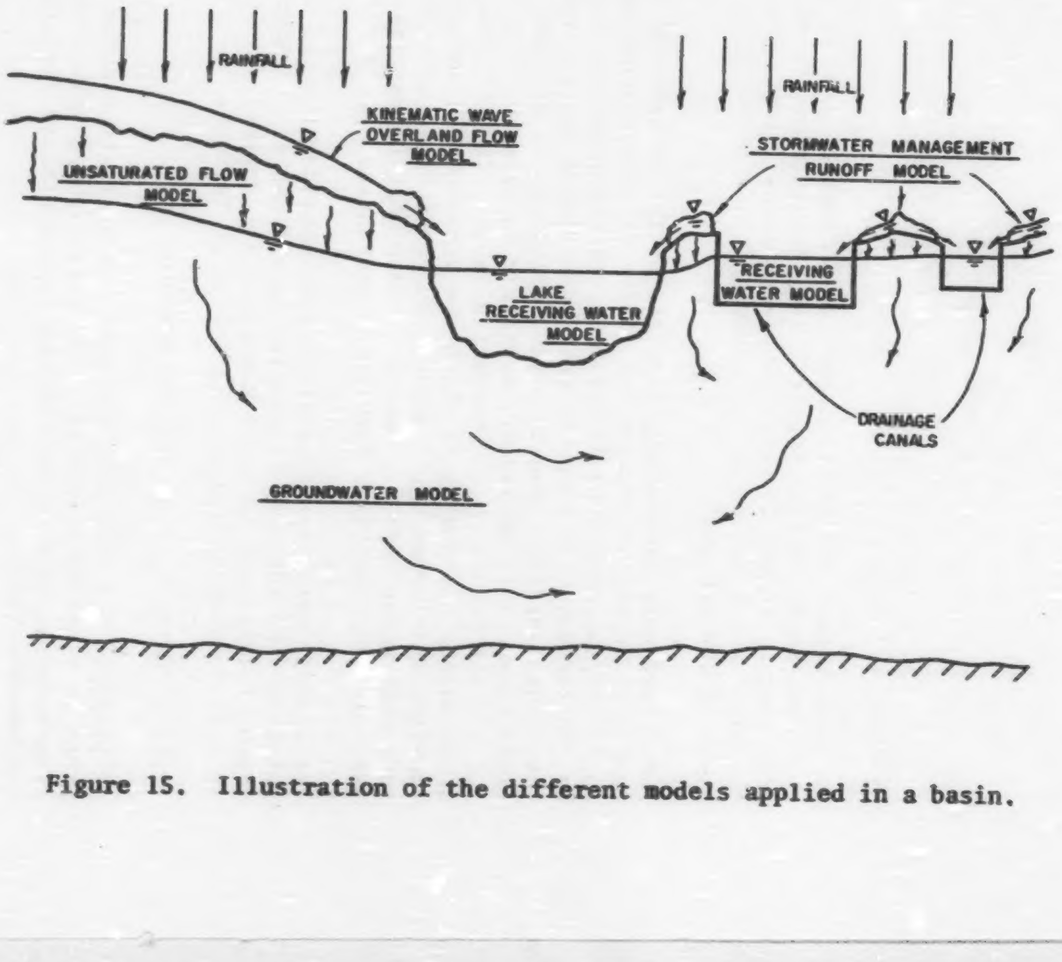

RAINFALL
RAINFALL
KINEMATIC WAVE
OVERLAND FLOW
MODEL
UNSATURATED FLOW
MODEL
STORMWATER MANAGEMENT
RUNOFF MODEL
LAKE
RECEIVING WATER
MODEL
RECEIVING
WATER MODEL
DRAINAGE
CANALS
GROUNDWATER MODEL

Figure 15. Illustration of the different models applied in a basin.

between the different models, the various runs should provide insight into sensitivity aspects. The relative impact of any given model upon another will depend upon the particular basic under study. However, it is still possible to propose some generalizations on sensitivity which should hold under most circumstances. For instance, short-term infiltration rates in the unsaturated flow model should produce relatively little impact on the overall groundwater flow patterns, which are long-term results of basin geometry and permeability configuration (Freeze, 1969). On the other hand, the infiltration rates following a rainstorm should have a profound effect on the ensuing overland flow (Agricultural Research Service, 1971).

In addition to the need for more detailed analyses of model interactions in any given basin, it is anticipated that improvements in the individual formulations might be desirable. To facilitate the introduction of these improvements in the future, an effort was made to maintain the computer models as self-sustaining entities, linked together by a relatively flexible set of interfacing instructions.

More specifically, it appears that one of the basic problems that will require increased attention is that of estimation of model parameters, such as permeability. At present, several optimization techniques have been employed to estimate permeabilities in groundwater systems, e.g., Kleinecke (1971). It might become desirable to extend the use of these techniques on a basin-wide basis. In that case, it is likely that the overall calibration task might best be accomplished by using a decomposition, rather than a unified, approach.

In summary, this discussion has pointed out the need to preserve the identity of the various computer models, at least until an improved state of the art permits the development of a single, global model. Thus, the decision at hand consists of determining the order in which the models are to be activated. It might be recalled that each hydrologic model has a water quality counterpart, which must be run immediately following the flow computations. Therefore the sequential uncertainty involves only the hydrologic processes.

INTERFACING STRATEGY

Spatial and Temporal Factors

At this point, it pertinent to discuss the significance of the matter of flow paths with respect to the two basic mathematical approaches to fluid mechanics. The first of these, the Lagrangian method, follows the spatial coordinates of a given fluid parcel as it moves with time. The alternate Eulerian approach describes temporal changes in fluid motion at prespecified locations in the system (Li and Lam, 1964). The latter approach has been widely considered to be more convenient and it underlies most available computer models, including those used in this study. Accordingly, a detailed treatment herein of particle paths was considered to be unwarranted. In future efforts, it might be worthwhile to utilize the Lagrangian technique for processes such as runoff quality, in which soil particles may undergo successive cycles of scouring and settling. In this study, however, the use of any time history information is restricted to the determination of boundary conditions between the various hydrologic regimes in a basin.

Since the accurate estimation of boundary conditions plays a significant role in determining overall predictive success, it is important to consider the interplay of these conditions in establishing the stepwise procedure for calling the various models. One immediate problem in this regard is the determination of which model should be run first. Intuitively, it seems that the model in question should be one whose main boundary conditions occur early in the hydrologic chain of events. Another desirable feature of this model would be its relative insensitivity to short-term feedback from other models. In this study, the initial model selected was that for the unsaturated zone, which is thought to be the likely choice for most basins. Illustration of the basic features of this model, including its boundary conditions, is given in Figure 9.

Unsaturated Zone Model

The top two boundary conditions in this model, rainfall and evaporation, are among the better known variables in any hydrologic system. Under conditions of high rainfall intensity, a ponding situation will arise at the ground surface, and in this case the formulation will require the setting of a maximum ponding depth (Freeze, 1969). The determination of this value is a somewhat arbitrary process, but any reasonable value will result in a hydraulic gradient which approaches unity in the vicinity of the ground surface. That is, unless the node spacing, Δz, is very small, the value of the hydraulic gradient at the upper nodes should be relatively insensitive to the maximum ponding depth used.

The bottom boundary flow in the soil profile is equal to the net recharge into the groundwater system. It is proposed that an initial recharge rate be obtained prior to running the unsaturated model, in the following stepwise fashion: (1) conduct several runs of the groundwater flow model under a variety of water table elevations; (2) store the computed sets of recharge velocities at the upper groundwater system nodes; and (3) select the recharge value corresponding to the initial water table location used for the unsaturated model. This bottom boundary condition is assumed to remain constant over relatively short-term changes in the vertical soil profile, including saturation of some nodes. The justification for this assumption lies in the fact that groundwater flow systems are sluggish in responding to external conditions, and are thus unlikely to produce significant short-term feedback.

Finally, some initial conditions must be specified in the unsaturated model. In the flow portion of the formulation, these conditions consist of moisture content values at the various nodes in the soil profile. It is difficult to determine these values exactly except by direct measurement, but it should be possible to provide reasonable estimates based on basin hydrology and land use. For instance, in agricultural areas it is common practice to maintain the soil moisture near field capacity (0.1 atmospheres) to facilitate water uptake by crops (Choate and Harrison, 1968). This objective is generally achieved by providing sufficient irrigation water to offset evaporative losses from the soil. In uncultivated soils, evaporative losses during dry periods typically produce a moisture profile in which the moisture content decreases with elevation (Freeze, 1969). If a no-flow condition were to exist within the soil, the total head at all nodes would be the same. Thus, changes in elevation head between nodes would be offset by opposite and equal changes in pressure head.

In the water quality portion of the unsaturated zone model, the main boundary condition is that which specifies the amounts of substances made available by man's activities on the ground surface. In this study, this type of boundary condition is set at the uppermost node by specifying the concentrations of nitrogen and phosphorous originating from fertilizer application. A discussion of references on other agricultural sources of nutrients, such as animal wastes, is provided in Appendix F. Also, the nutrient contents of rain water have been found to be significant by some investigators (Weibel et al., 1966). If such a contribution is to be accounted for by means of another surface boundary condition, it is advisable to utilize rainfall quality data collected at the particular basin in question. In addition to boundary conditions, the quality model requires the specification of initial conditions, in the form of concentrations at the various nodes. These values can only be estimated roughly in the absence of field data.

It may be concluded that the unsaturated zone model plays an important role in the overall system, in the capacity of a link, or buffer, between the surface and groundwater regimes.

Surface and Groundwater Models

The degree of connection between surface and groundwater systems depends largely on whether a recharge or discharge condition exists. Under a recharge situation, the two systems are generally separated by the unsaturated zone, as can be seen in Figure 15. Consequently, it is possible to consider the surface and groundwater regimes in a quasi-independent fashion. That is, any feedback between the two regimes is transmitted only indirectly through the unsaturated zone model.

On the other hand, groundwater discharge to surface bodies of water occurs directly. This is the case with base flow in streams and upflow in springs, for instance. Thus, the corresponding modeling approach is somewhat different.

Since the unsaturated zone model was selected in this study as the first one to be run in the modeling cycle, the question remained as to which system should be considered next, surface or ground water. In view of the fact that changes occur much more rapidly in the surface system than in ground water, the order developed consisted of the surface followed by ground water. The overland flow and groundwater models utilize information generated by the unsaturated zone formulation in the vicinity of its top and bottom nodes, respectively.

The surface water processes are covered by two overland flow models and the receiving model. The first overland flow formulation and the receiving model are modified versions of those found in the Stormwater Management Model (Environmental Protection Agency, 1971). This overland flow formulation is proposed for use in areas where artificial drainage and channelization are widespread. The second overland flow model, to be utilized in relatively undeveloped areas, is based on the kinematic wave approach (Eagleson, 1970). The types of areas in which these two approaches are utilized are illustrated in Figure 15.

In both overland flow formulations, the infiltration rates (flows between the two upper nodes) obtained from the unsaturated zone model are used in conjunction with rainfall hyetographs to calculate flow hydrographs at the various catchment outlets. Also computed at the outlets are nutrient transport rates. This flow and quality information is in turn used as input to the receving water model.

Turning to the groundwater model, it receives input from the unsaturated zone model in the form of water table elevations and concentrations of nutrients at the bottom node of the soil profile. Following heavy rainstorms, it is possible that the soil profile may become saturated throughout. In any case, the groundwater model utilizes the computed water table elevation as a boundary condition at the end of the unsaturated zone simulation period. At the same time, the groundwater model takes into account flow information at the boundaries which are not linked with other models, such as the bottom horizontal boundary. After the velocity field has been computed, the convection-dispersion formulation routes the movement of nutrients located at the bottom of the unsaturated zone.

PROGRAMMING AND USAGE ASPECTS

Figure 16, constitutes a flow diagram involving the various formulations. Beginning at the upper portion of this figure with the unsaturated zone model, the computations are next carried out for the overland flow and receiving models. The calculations for the latter two models are branched out, depending upon whether or not man-made drainage is prevalent in any given area. Finally, the groundwater computations are completed.

The dotted arrows in Figure 16 denote the interfacing or boundary condition data which are transferred between any two models. These data consist typically of hydraulic heads, velocities and concentrations. Some of the specific items are indicated in the figure. Changes in the linkage structure might be deemed desirable depending upon local conditions.

From a programming standpoint, it becomes apparent that the stepwise computational procedure shown in Figure 16 should be controlled by a main, or executive, program. Accordingly, the individual computer models become subroutines (sub-programs) of this main program. In turn, each model subroutine contains other smaller subroutines.

With regard to data storage and retrieval, two alternate programming techniques were considered. The first consisted of the specification of various data storage areas which would be shared by two or more subroutines. The advantage of the use of these storage areas, technically known as COMMON blocks, is that computed values are transferred implicitly between the pertinent subroutines, without the need for input/output instructions. However, the main drawback of this method lies in the fact that its total storage requirements for a basin of reasonable size can approach or exceed the capacity of the computer facilities. This was the case with the University of Florida system, an IBM 360/65 with a total capacity of approximately one million bytes. Since this is a comparatively large system, the storage problem is likely to be aggravated at most facilities elsewhere. Accordingly, the use of COMMON blocks was restricted to internal linkages between the quantity and quality portions of each model, and another method was sought for transfers between these major models.

The alternate approach used, designed to minimize storage utilization, is known as an overlay technique. The effect of this method is that, at any time in a computer run, the storage being utilized involves only the main program and the particular model subroutine being executed. Following the execution of a given model, its results must be stored for subsequent use by another model. For this purpose, active computer storage is not used, but rather an external unit

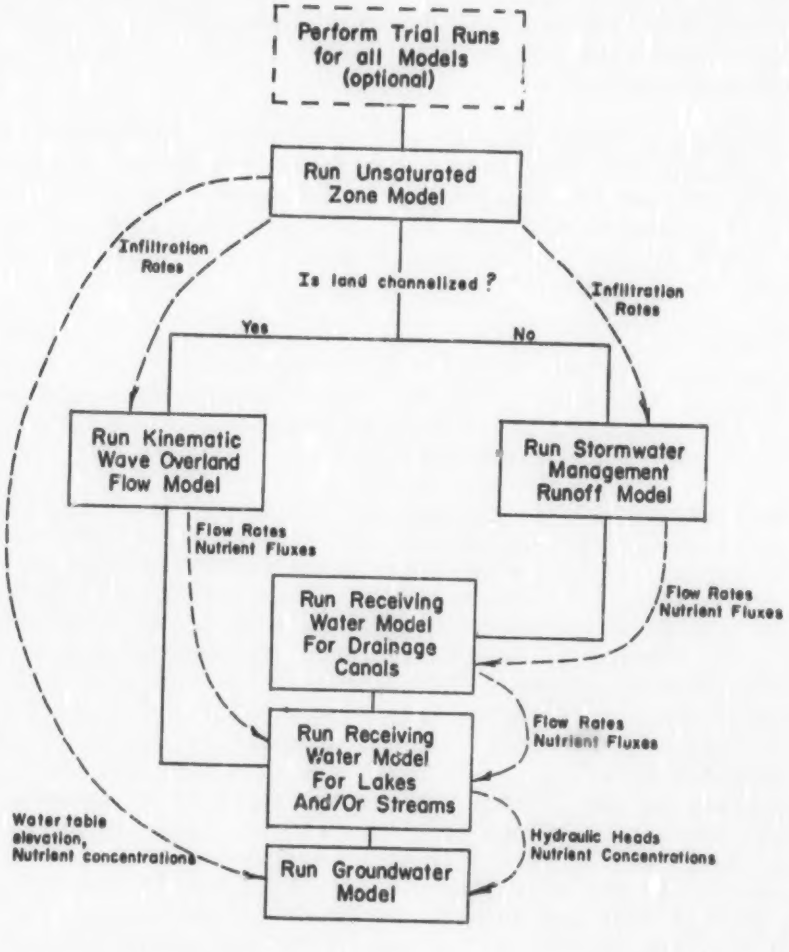

Perform Trial Runs for all Models (optional)
Run Unsaturated Zone Model
Infiltration Rates
Is land channelized ?
Infiltration Rates
Yes
No
Run Kinematic Wave Overland Flow Model
Run Stormwater Management Runoff Model
Flow Rates Nutrient Fluxes
Flow Rates Nutrient Fluxes
Run Receiving Water Model For Drainage Canals
Flow Rates Nutrient Fluxes
Run Receiving Water Model For Lakes And/Or Streams
Water table elevation, Nutrient concentrations
Hydraulic Heads Nutrient Concentrations
Run Groundwater Model

Figure 16. Flow diagram for the various models, illustrating data interfacing.

utilized. The unit in question, known as a data set (DATA SET) is operated in a fashion similar to that of a tape, but has the advantage of more rapid access. The use of the overlay procedure and a data set is illustrated in Figure 17.

Appropriate WRITE/READ statements must be included in the model subroutines to transfer data to and from data sets, respectively. A large number of data sets may be used in connection with a given program. A given data set may be used successively to store different variables, and in this case it must be designated as temporary, or scratch. On the other hand, a permanent data set may be created for data transfer exclusively between two given model subroutines.

Additional details on the use of data sets within an executive program are provided in Appendix D. Also contained are the job control language (JCL) instructions used. These JCL statements will require modifications prior to usage in other computer facilities.

TIME INCREMENTS AND SPATIAL PARTITIONING

Due to the significant expense involved in running the computer package, it is infeasible to utilize it on a continuous basis. Instead, it is advisable to reserve its use to simulate the effect of significant events, such as a high intensity rainfall following the application of fertilizer.

It is important to note that, while the simulation periods for all the models shown in Figure 16 begin at the same point in time, the total length of these periods need not be the same. For instance, the overland flow model might be run only for several hours, but the receiving model might be run for several days thereafter to allow sufficient time for significant pollutant movement.

Also, a wide difference in the significance of the time element exists between the flow and quality portions of the groundwater model. Since the former is relatively insensitive to short-term changes in flow boundary conditions, it should seldom be justified to run it with a frequency greater than, for instance, once a month. That is, the velocity field could be considered invariant within such a period.

However, to adequately trace the impact of a given input of pollutants to a groundwater system, the total simulation time required would be in the order of months and years. Thus, in strict terms, the use of several velocity fields would be required in addition to that in existence at the time of the pollutant input.

It follows that discrepancies also exist with regard to the length of time increments used in the various models. As a rule, the models which

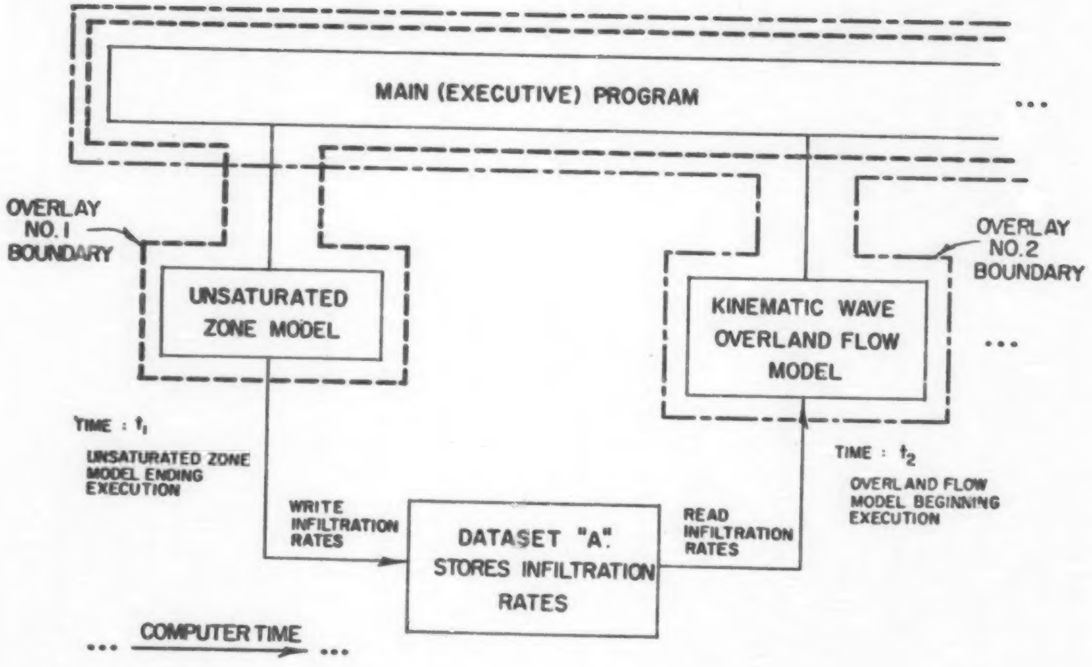

MAIN (EXECUTIVE) PROGRAM
...
OVERLAY NO. 1 BOUNDARY
UNSATURATED ZONE MODEL
KINEMATIC WAVE OVERLAND FLOW MODEL
OVERLAY NO. 2 BOUNDARY
...
TIME : t_1
UNSATURATED ZONE MODEL ENDING EXECUTION
TIME : t_2
OVERLAND FLOW MODEL BEGINNING EXECUTION
WRITE INFILTRATION RATES
DATASET "A": STORES INFILTRATION RATES
READ INFILTRATION RATES
... COMPUTER TIME ...

Figure 17. Schematic representation of the use of overlay technique with data sets.

are run earlier in the package are those which utilize the shorter time steps. Thus, the results of the overland flow model, for instance, must be averaged over longer intervals prior to transfer into the receiving model. This averaging process is shown in Figure 18.

It is also pertinent to point out the interfacing complexities introduced by partitioning the physical region to which a given class of model applies. Schematically, this concept of partitioning was first presented in Figure 16, in which the overland flow calculations are branched out to indicate two different types of surface terrain: (1) artificially drained (channelized) land and (2) nonchannelized areas. In a typical basin, it is likely that these two types will be interspersed, effectively producing proliferation of branches at the level of overland flow calculations. Similarly, the areal partitioning of the unsaturated zone on the basis of soil classification will produce branching at that level. Care must be taken to insure that a proper interfacing between the various model branches is conducted.

It would be difficult to further illustrate the above comments on temporal and spatial aspects of interfacing without reference to a specific study area. For this reason, additional discussion of these matters is deferred to Section VIII, involving the Lake Apopka basin.

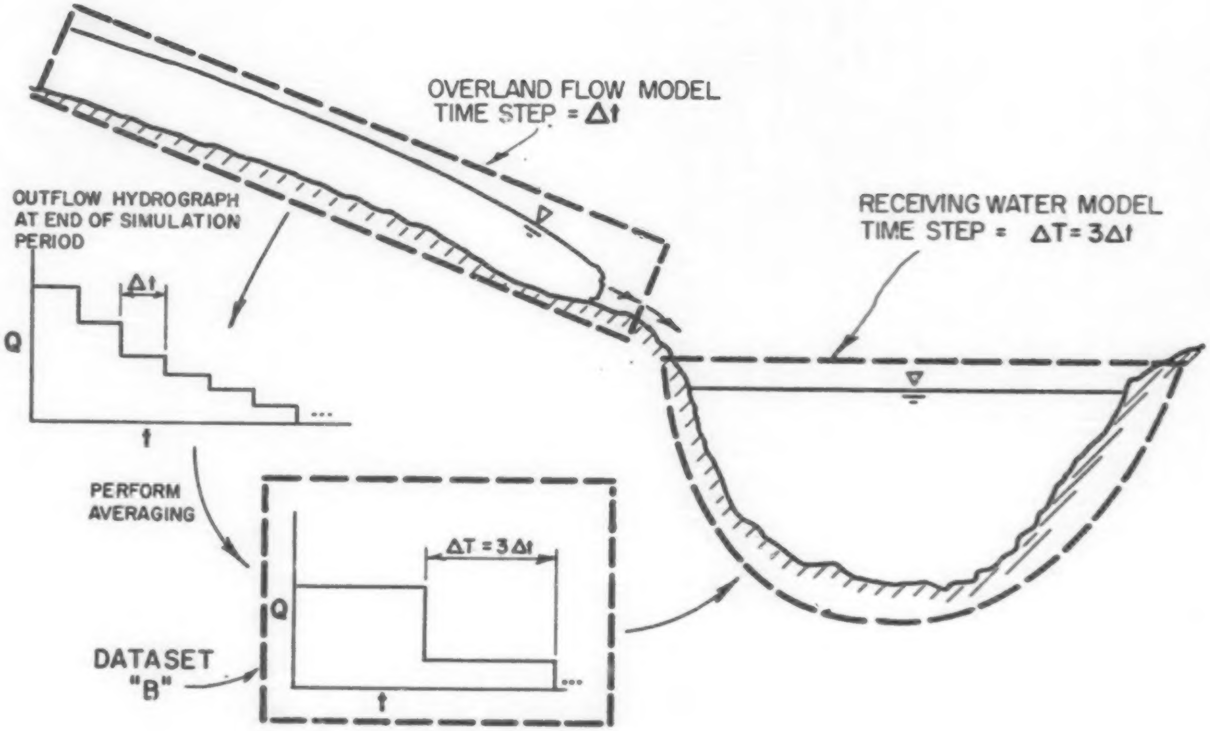

OVERLAND FLOW MODEL
TIME STEP = Δt
OUTFLOW HYDROGRAPH AT END OF SIMULATION PERIOD
Q
Δt
t
RECEIVING WATER MODEL
TIME STEP = ΔT = 3Δt
PERFORM AVERAGING
ΔT = 3Δt
Q
t
DATASET "B"

Figure 18. Schematic representation of time-averaging process for interfacing flows between overland flow and receiving models.

SECTION VIII

APPLICATION TO THE STUDY AREA

INTRODUCTION

Prior to discussing the application of the computer model package to the Lake Apopka basin in Central Florida, it is worthwhile to review some general aspects of the various models and their interfacing methodology. A schematic representation of the executive, or main, program and the order of its individual model subroutines is provided in Figure 19. Also illustrated in this figure is the use of data sets for input/output operations between models.

In Appendices A, B and C, sample calculations for the different models are illustrated using hypothetical data. Additional insight into these calculations will be provided by discussions on the usage of data from the study area. It must be emphasized that the scope of this study precluded a sampling program. Whenever necessary, values were obtained from the literature, and some of these were modified to reflect specific conditions in the Lake Apopka basin. Most of the assumptions in agricultural calculations were formulated following personal communications with research personnel of the University of Florida Institute of Food and Agricultural Sciences (IFAS).

One interfacing aspect which requires much judgment is the partitioning of the basin into relatively homogeneous units, to improve the predictive quality of the various models. For instance, the unsaturated zone can be partitioned according to soil type, among other possibilities. For any given model, this spatial division process could be carried out by either one of two methods: (1) reusing the same program for all the pertinent partitions, in each case utilizing the appropriate parameters; and (2) making available a separate program for each partition, and imbedding the necessary parameters within each program. While the latter method minimizes the transfer and storage of data, the former is more efficient from a computational standpoint.

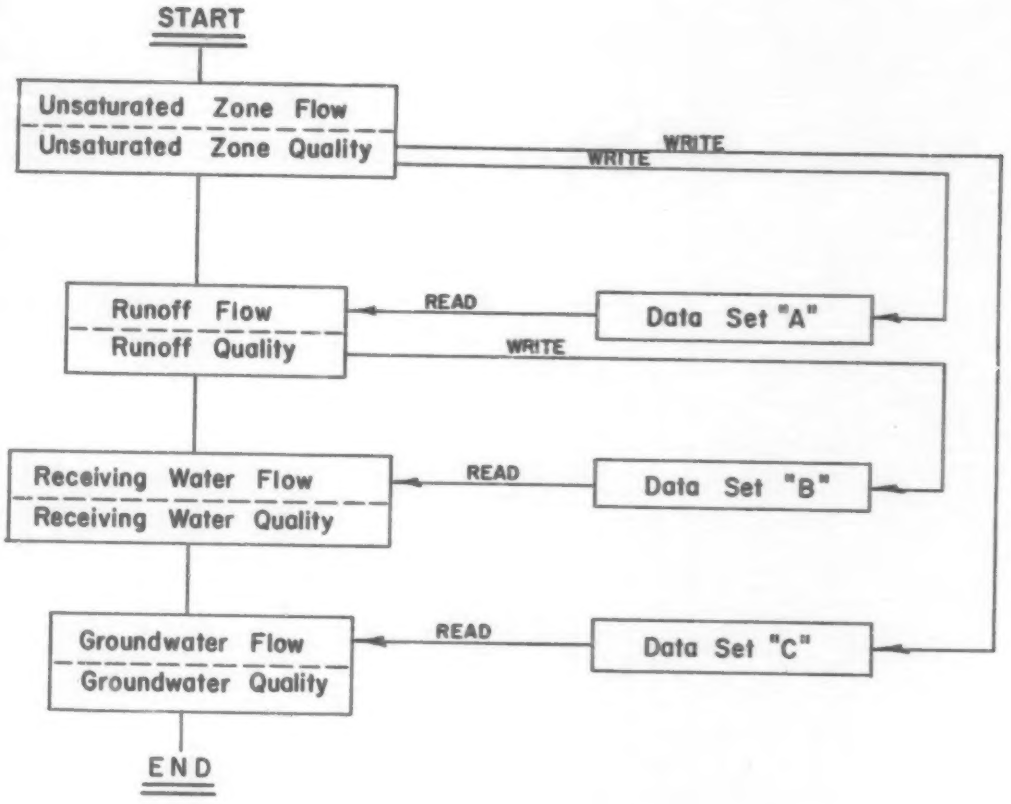

START
Unsaturated Zone Flow
Unsaturated Zone Quality
WRITE
WRITE
Runoff Flow
Runoff Quality
READ
Data Set "A"
WRITE
Receiving Water Flow
Receiving Water Quality
READ
Data Set "B"
Groundwater Flow
Groundwater Quality
READ
Data Set "C"
END

Figure 19. Illustration of the types of models in the executive program and the use of data sets for interfacing.

Both of the above approaches are applied to the study area. For example, method (1) is used in connection with the various catchments in the kinematic wave overland flow model. On the other hand, method (2) is applied to the unsaturated zone.

The next item to be discussed consists of a description of the study area, involving both geographic and water quality aspects. Nitrogen and phosphorous are the main quality parameters considered. Each model is then discussed individually. Subsequently, the interfacing methodology is explained further, with emphasis on partitioning aspects. Finally, objectives considered in devising various simulation runs are presented.

DESCRIPTION OF THE STUDY AREA

Location and Size

The Lake Apopka basin is located in the central portion of the State of Florida, approximately 15 miles (24 km) west of the city of Orlando (see Figure 3). A map of the basin, showing its drainage boundary, is provided in Figure 20. The drainage divide lies much closer to the southern shore of the lake than that originally proposed by the U.S. Geological Survey (Lichtler, Anderson and Joyner, 1968). One reason for this modification is that the southern divide used is a secondary topographic ridge, which should nevertheless constitute the lake's effective overland flow drainage boundary for most rainstorms. Also, any subsurface contributions from the omitted area could be accounted for by specifying boundary conditions beneath the selected divide. Accordingly, the effective basin area considered was reduced from the U.S.G.S. estimate of 180 square miles (461 km^2) to approximately 120 square miles (307 km^2).

As can be observed, Lake Apopka occupies a relatively large portion of the basin. Its surface area is about 30,000 acres (120 km^2) and its mean depth is only 6 feet (1.8 m) (Sheffield and Kuhrt, 1969). The mean stage of the lake is 67 feet (20 m) M.S.L.

General Hydrology

The mean annual temperature at Orlando, Florida is 71.5°F (22°C) and the average yearly rainfall is 51.4 inches (131 cm) (Lichtler, Anderson and Joyner, 1968). Studies conducted for Orange County (Anderson and Joyner, 1966), on which most of the basin lies, indicate that about 70 percent of the rain falling on the county returns to the atmosphere by evaporation and transpiration. The remaining 30 percent is broken down as follows: approximately two-thirds flows out of Orange County as surface runoff and one-third flows out under ground. These figures are presented only with the purpose of providing some insight into

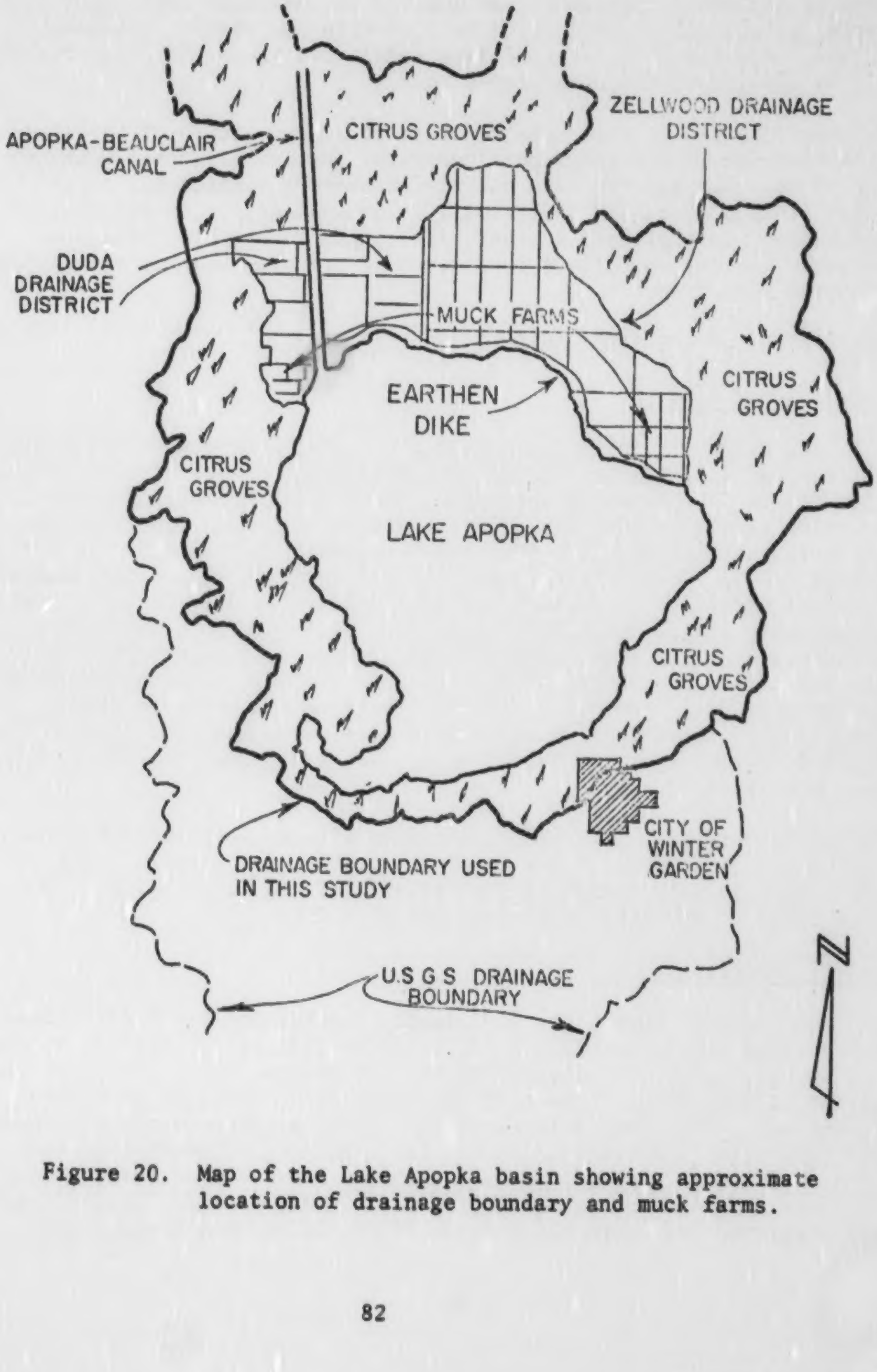

APOPKA-BEAUCLAIR CANAL
CITRUS GROVES
ZELLWOOD DRAINAGE DISTRICT
DUDA DRAINAGE DISTRICT
MUCK FARMS
EARTHEN DIKE
CITRUS GROVES
CITRUS GROVES
LAKE APOPKA
CITRUS GROVES
CITY OF WINTER GARDEN
DRAINAGE BOUNDARY USED IN THIS STUDY
U.S G S DRAINAGE BOUNDARY
N

Figure 20. Map of the Lake Apopka basin showing approximate location of drainage boundary and muck farms.

general conditions in the area. More specific information on rainfall and evaporation rates is available from various gaging stations. Hydrologic budgeting efforts conducted within the Lake Apopka basin are discussed briefly in subsequent sections and in Appendix E.

Natural Features and Human Activities

For modeling purposes, the hydrologic system was broken down into three regimes: (1) surface waters, (2) unsaturated zone and (3) groundwater zone.

Surface Waters—

As a whole, the topography of the basin is of gentle relief, but it varies locally depending upon the type of soil. The areas east, west and south of Lake Apopka, shown in Figure 21, are underlain by sandy soils and for the most part are utilized for the cultivation of citrus. Chemical fertilizers are used in these farming operations. The terrain in these citrus areas undulates, with a maximum elevation of 250 feet (76 m) M.S.L. Due to the large number of ridges and local depressions, the overland flow pattern is quite complex. For rainstorms of moderate intensity, only a small portion of the total citrus area should contribute overland flow to Lake Apopka. That is, the contributing catchments would be only those located in the vicinity of the lake shores.

In contrast to the undulating topography of the sandy soils, the land located on the north shore of the lake exhibits an almost completely flat surface. This region (see Figure 20), originally a part of the lake's littoral zone, was reclaimed by drainage during the 1940s for farming purposes (Sheffield and Kuhrt, 1969). It is composed of a nutrient-rich organic soil known as muck. The total area of the muck farms is approximately 18,000 acres (72 km^2), or about one-third of the original lake surface area.

Natural, periodic inundation of the muck lowlands has been prevented by the construction of an earthen dike along the north shore of Lake Apopka. A drainage system, composed of mole drains, canals and pumps has been developed to transport excess rain water into the lake. The nitrogen and phosphorous contents of this drainage water are generally high (Sheffield and Kuhrt, 1969). These nutrients originate from fertilizers and also from the muck soil itself.

In addition to farming activities, other man-made effects, shown in Figure 21, are manifest in the basin. One of these is the Apopka-Beauclair Canal, constructed in 1948 to withdraw water from Lake Apopka. With the construction of a lock structure in the canal four years later, the lake became a managed reservoir (Sheffield and Kuhrt, 1969). The small city of Winter Garden, located on the southeastern

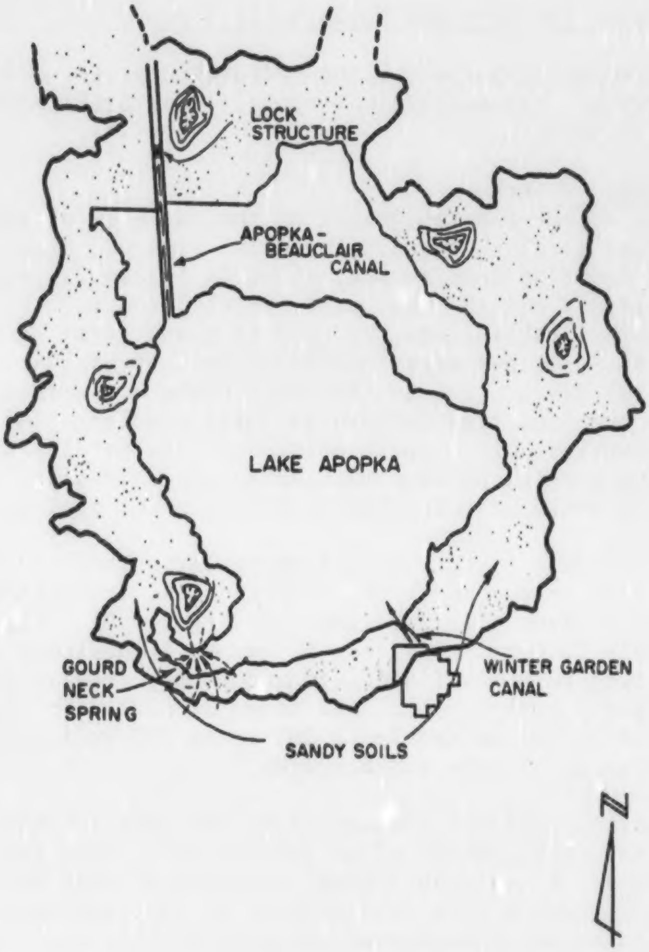

LOCK STRUCTURE
APOPKA-BEAUCLAIR CANAL
LAKE APOPKA
GOURD NECK SPRING
WINTER GARDEN CANAL
SANDY SOILS
N

Figure 21. Illustration of the topographic features of the sandy soils and other hydrologic features in the Lake Apopka basin.

shore of the lake, discharges treated municipal and citrus processing waste water into Lake Apopka.

Another source of flow and associated nutrients to Lake Apopka is Gourd Neck Spring, located on the southwestern tip of the lake. The spring water is thought to originate from a highly permeable deep formation, known as the Floridan Aquifer (Anderson, 1971). Lake water quality samples taken by the Orange County Pollution Control Department in the vicinity of the spring suggest that its nitrogen contribution is greater than its contribution of phosphorous.

Unsaturated Zone—
The movement of water through the unsaturated zone strongly depends upon the type of soil present. Literature data from Florida on the two predominant soil types in the basin, muck (Harrison and Weaver, 1968) and fine sand (Stewart, Powell and Hammond, 1963) indicate their large capacity to transmit water under saturated conditions. Under unsaturated conditions, which constitute the general case, hydraulic conductivities decrease appreciably with decreasing water content. Unfortunately, very little quantitative information on unsaturated flow relationships is available for the two soils under consideration.

The thickness of the unsaturated zone (vertical distance between ground surface and water table) can be estimated at different locations from U.S. Geological Survey data on shallow observation wells. In the Lake Apopka basin, the water table is relatively flat, indicating the lack of appreciable moisture gradients in the horizontal direction of the unsaturated soil zone. For this reason, the use of a one-dimensional flow model (Freeze, 1969) for this zone was thought to be justified. Additional schematic information on the unsaturated zone will be provided in other discussions.

Groundwater Zone—
Two main geologic formations exist in the basin: (1) a shallow stratum composed of sand and clays (clastics) with some low permeability layers; and (2) a deep formation composed of highly permeable limestone, known as the Floridan Aquifer (Lichtler, Anderson and Joyner, 1968). Data collected by the U.S.G.S. in Orange County (Lichtler and Joyner, 1966) indicate that the thickness of the clastic formation fluctuates around 100 feet (30.5 m) in the vicinity of Lake Apopka.

Flow in the Floridan Aquifer occurs predominantly in the horizontal direction, with the exception of a significant vertical component in the Gourd Neck Springs area. A typical piezometric map for this aquifer is provided in Figure 22. It indicates that the general direction of flow is from southwest to northeast.

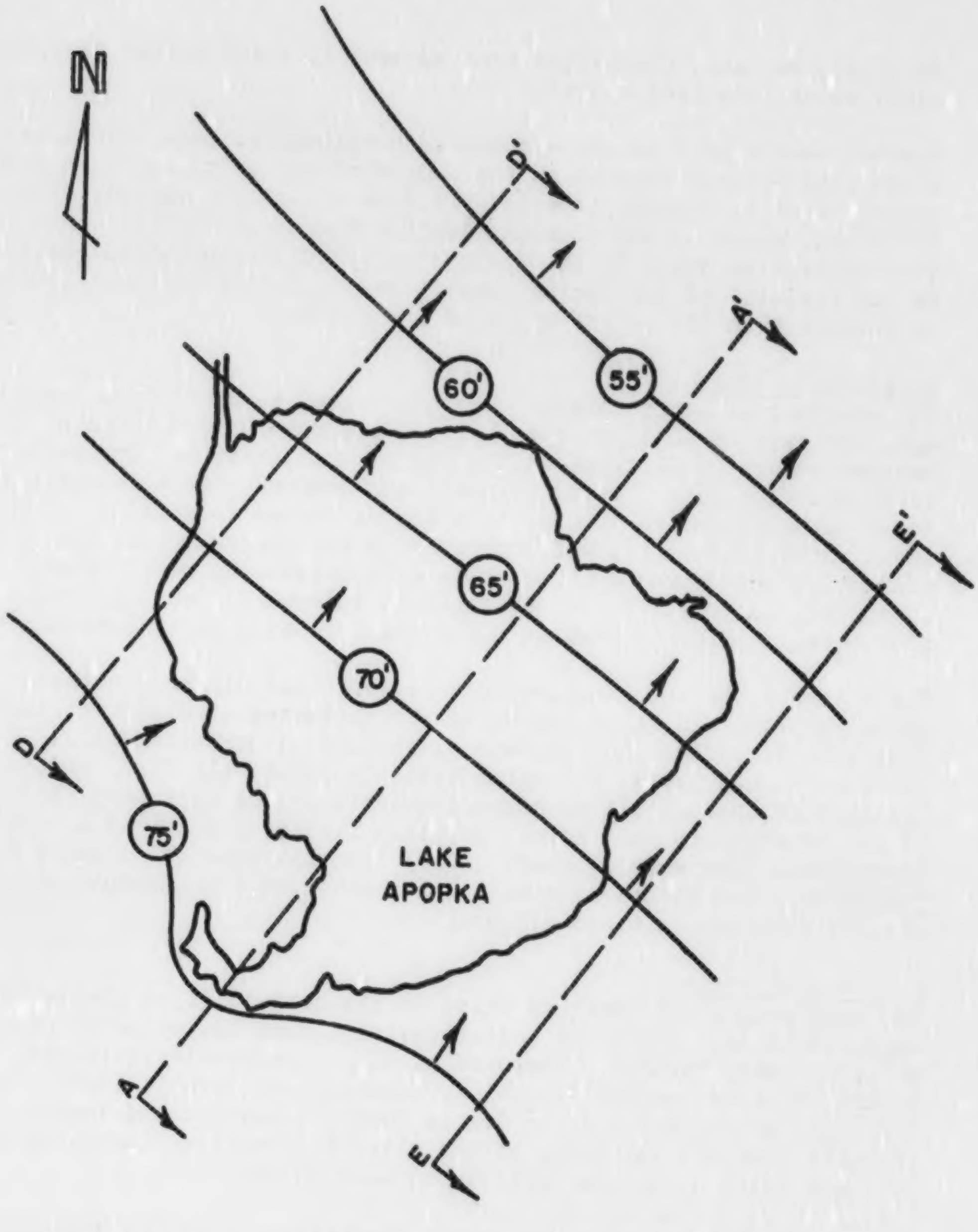

N
D'
A'
E'
55'
60'
65'
70'
75'
LAKE
APOPKA
D
A
E

Figure 22. Typical piezometric contours, (ft), in the Floridan Aquifer. Lake Apopka is only weakly connected to the aquifer at Gourd Neck Springs. Hence, piezometric values are not constant across the lake. Vertical cross-sections conform to two-dimensional flow within the Floridan Aquifer.

The hydraulic head at a given location in the Floridan Aquifer is not constant, but varies seasonally in response to rainfall patterns (Lichtler and Joyner, 1966). The extent of these fluctuations depends upon factors such as degree of proximity to recharge areas. However, a comparison of piezometric countours at low-water, normal and high-water conditions (Lichtler, Anderson and Joyner, 1968) indicated relatively little change in the general direction of flow. This conclusion is less likely to be valid in basins where seasonal pumpage effects are significant.

For modeling purposes, it is necessary to consider the selection of geologic cross sections satisfying the condition of two-dimensional flow (Freeze and Witherspoon, 1966). An examination of Figure 22 reveals that a large number of roughly parallel sections could be drawn for the Floridan Aquifer along the dip of its piezometric surface. Some of the possible choices, valid only for this formation, are illustrated.

For a more complete examination of the system, however, it is desirable to locate vertical cross sections which include all geologic strata of interest. Accordingly, consideration of conditions in the overlying clastic formation becomes necessary. Referring to Figure 24, a rough assumption can be made that in the shallow groundwater system, the horizontal component of flow occurs radially into or out of Lake Apopka. A review of ground surface contours and U.S.G.S. shallow well data for the citrus areas indicates that this horizontal component is oriented toward the lake. On the north shore, the fact that the ground elevation of the muck farms is only 65 feet (20 m) M.S.L., or 2 feet (0.6 m) lower than the mean lake stage, points out that some flow must occur from the lake to the farms. The directions of horizontal flow components in the shallow zone, described above, are shown in Figure 23.

Given the flow patterns in both the shallow and deep formations, it was possible to select a vertical cross section for analysis. The location of this section, labeled as AA', is shown in Figure 23. A lateral view of AA' is provided in Figure 24. The location of the approximate boundary between the shallow stratum and the Floridan Aquifer is shown. It is recognized that this aquifer extends downward several hundred feet but, for practical reasons, an artificial bottom boundary was defined as shown.

It may be observed that the vertical thickness of the unsaturated zone varies considerably along the cross section. In the southwestern portion , the water table surface is just slightly higher than the piezometric surface of the Floridan Aquifer, shown in Figure 22. In the muck farm areas, the water table, controlled by artificial drainage methods, lies approximately 2 feet (0.6 m) below the ground.

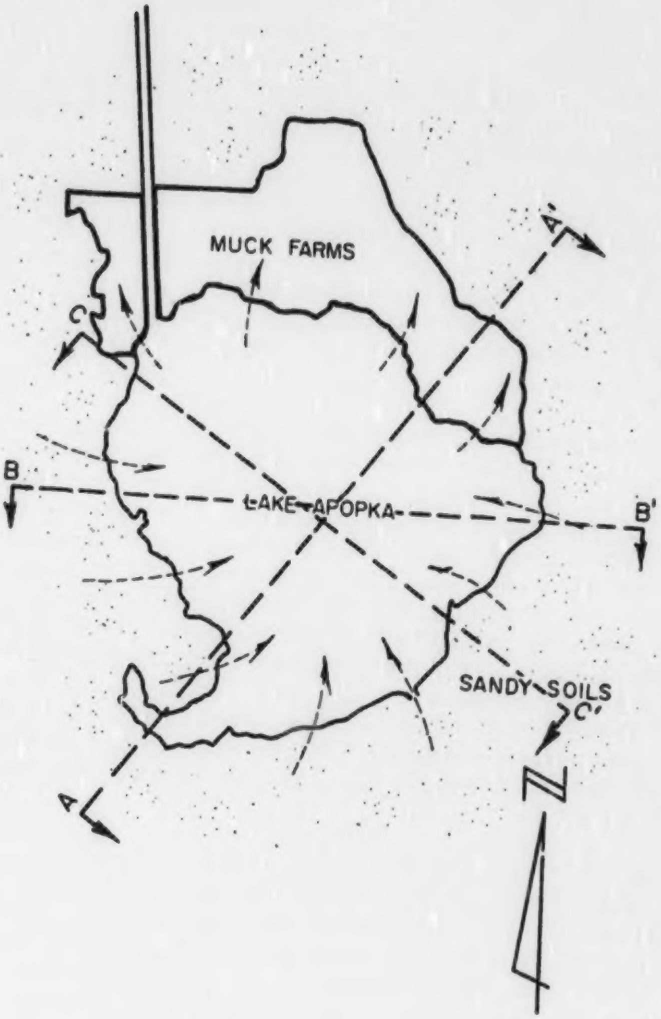

MUCK FARMS
LAKE APOPKA
SANDY SOILS
A
A'
B
B'
C
C'
N

Figure 23. Directions of horizontal flow components within the shallow formations, inferred from topographic data. Also indicated are main and auxilliary cross-sections selected for analysis.

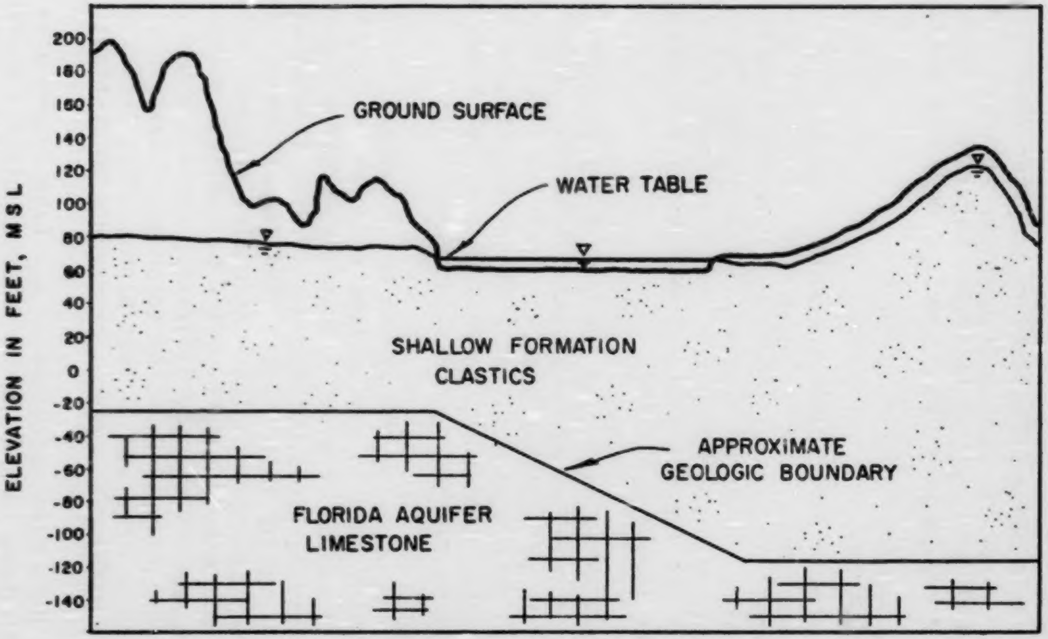

ELEVATION IN FEET, MSL
200
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
GROUND SURFACE
WATER TABLE
SHALLOW FORMATION CLASTICS
APPROXIMATE GEOLOGIC BOUNDARY
FLORIDA AQUIFER LIMESTONE

Figure 24. Lateral view of cross-section AA', (Figure 23).

Finally, the thickness of the unsaturated zone for the region northeast of the muck farms is assumed to be approximately 5 feet (1.5 m). Additional data on this cross section, including permeability estimates, are provided in subsequent sections.

In Figure 23, sections BB' and CC' were other original candidates for analysis. These sections extended downward only through the clastic formations, since their orientation would preclude their validity within the Floridan Aquifer. Preliminary computer results indicated the existence of relatively little flow in the vicinity of Lake Apopka within both BB' and CC'. Due to their low degree of interaction with the lake, further analyses of these sections were not conducted.

WATER QUALITY STUDIES

Reports dating back to 1947 indicate a gradual decline of water quality conditions in Lake Apopka, mainly in the form of nutrient enrichment (Florida State Board of Health, 1964). In a recent statistical comparison of several lakes in Florida, Putnam *et al*. (1969) found Lake Apopka to be the most eutrophic. However, cause and effect relationships between the various external sources of nutrients and lake water quality are somewhat elusive.

Natural tendencies of lakes toward (or away from) eutrophy have been a subject of controversy among scientists (Brezonik, 1969). In the 1930s and 1940s the predominant view was that lakes follow a slow but irreversible path from their initial state of oligotrophy (low nutrient content) to eutrophy. According to this theory, man-made, or cultural, activities merely accelerate a natural process.

In recent years, an opposing theory has been proposed which states that lakes naturally tend to evolve from eutrophy to oligotrophy but that this process can be reversed by external processes such as man's activities (Mackereth, 1965; Hutchinson, 1969). Studies of lake core samples appear to verify this theory. Additional support for it derives from ecological principles. According to Odum (1969), the eutrophic state has many characteristics of immature ecosystems, such as low stability and low species diversity, while the reverse is true of the oligotrophic state. Thus, he reasoned, a lake should evolve toward the oligotrophic state if left alone. This latter theory offers encouragement to efforts to control or reverse eutrophication.

Several studies have been conducted in the Lake Apopka area to investigate the relative impact of the various nutrient sources on water quality. In 1968, Forbes reported the results of a sampling program to compare the nutrient levels in the muck farm canals to those in the lake itself. He pointed out the difficulty in establishing a cause

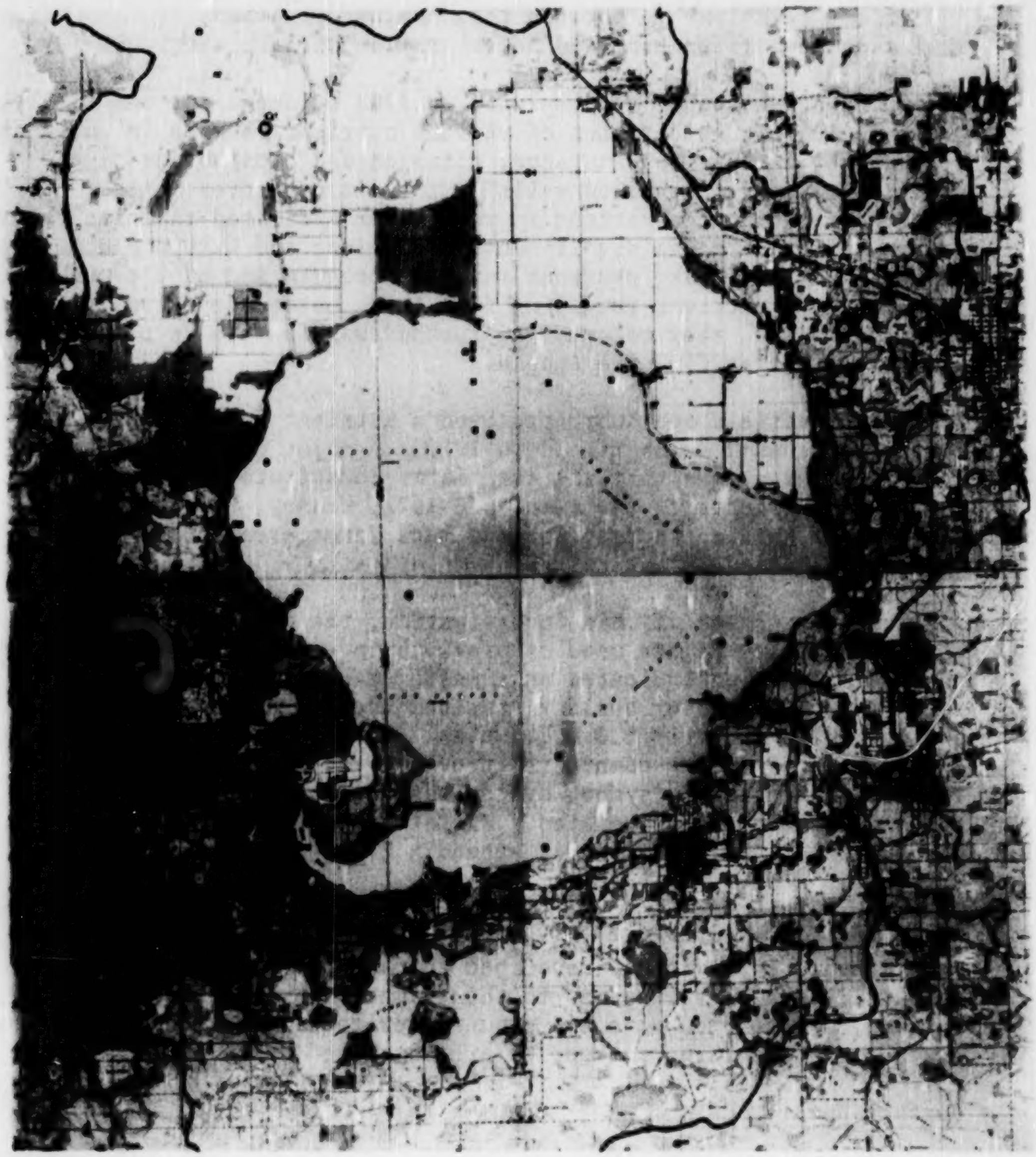


Figure 25. Reproduction of project map containing locations of various sampling points.

and effect relationship between the farming operations on the muck soil and the earlier reported deterioration of lake water quality.

A comprehensive study was completed in 1968 by Schneider and Little, which included consideration of various nutrient sources in addition to the muck farms. For instance, nitrogen and phosphorous samples were collected from shallow wells in the citrus groves. Also, measured nutrient concentrations in rain water indicated that its contribution to the lake was significant. Schneider and Little placed great emphasis on their lake sediment sampling program and on the probable importance of nutrient recycling from these bottom deposits to the lake water. Finally, they recommended further work on the development of a nutrient budget for Lake Apopka.

In 1969, Sheffield and Kuhrt proposed a nutrient budget, which was further discussed by Sheffield in 1970. A major conclusion derived from this budget was that the muck farms constituted the principal source of nutrients to the lake. In 1972, Heaney, Perez and Fox developed a nutrient budget for the muck farms area. This study is briefly discussed in Appendix E.

In the early phases of this investigation, the coordinates of the various sampling points used by previous investigators were established and their location indicated on a master map. The sampling points included surface water quality stations used by different agencies, shallow wells and deep U.S.G.S. wells. A reproduction of the project map with the sampling points is provided in Figure 25. To avoid confusion, a symbol system was developed for the different types of stations and agencies. A list of the various data sources used in this study is given in Appendix E.

USAGE OF MODELS

According to a previously developed format, the computer models in this study are classified as to their zone of applicability, namely; surface, unsaturated zone and groundwater zone. The model usage aspects for these three categories are discussed below.

Surface Water Models

The surface water processes considered are overland flow and flow in bodies of water. Two overland flow models have been discussed previously: (1) the kinematic wave formulation (Eagleson, 1970), and (2) the runoff portion of the Stormwater Management Model (Environmental Protection Agency, 1971). The latter model, originally developed for urban runoff systems, is relatively well suited for adaptation to agricultural areas in which the influences of man are greatly felt.

Thus, the Stormwater Management Model was selected for use in the highly channelized muck farms.

On the other hand, the kinematic wave model is better suited for areas with few artificial drainage controls. Accordingly, it was chosen for application to the sandy, undulating terrain.

It is recognized that, due to the high infiltrative capacity of both the muck and sandy soils, the phenomenon of overland flow appears to be of limited significance in the Lake Apopka basin. However, the application of the two model types was deemed desirable for illustrating their data requirements and interfacing aspects with other models.

The surface bodies of water considered were the drainage canals in the muck farms area and Lake Apopka itself. The receiving model portion of the Stormwater Management Model (Environmental Protection Agency, 1971) was utilized for the flow and quality computations in these bodies Further discussion on the applications of this model follows that on the overland flow formulations.

Kinematic Wave Model

Data Sources—

The terrain east, west and south of Lake Apopka (see Figure 22) is composed primarily of sandy soils. The predominance of this type of soil is shown in Figure 26, which consists of a soil classification map of the area. The map in this figure is a reproduction of a plastic overlay map developed from U.S. Soil Conservation Service data (1967) for Orange and Lake counties. The scale of the plastic overlay is the same as that of U.S. Geological Survey quadrangle maps (1:24000).

Also illustrated in Figure 21 are some of the numerous localized ridges and depressions, which result in a complex overland flow pattern. These topographic features are provided in detail in U.S.G.S. quadrangle maps. The undulating nature of the local topography indicated the need for partitioning the area into numerous idealized plane catchments.

Regarding land use, earlier reports (Schneider and Little, 1968; Sheffield and Kuhrt, 1969) have indicated that the main activity in this area is the cultivation of citrus. Since land use is an important factor affecting overland flow and water quality aspects, additional information was sought on other activities. One source of data consisted of aerial maps available from Soil Conservation Service soil surveys (1960). Another source consisted of acreage figures for various agricultural and nonagricultural uses, compiled also by the Soil Conservation Service (SCS). These figures, available from local

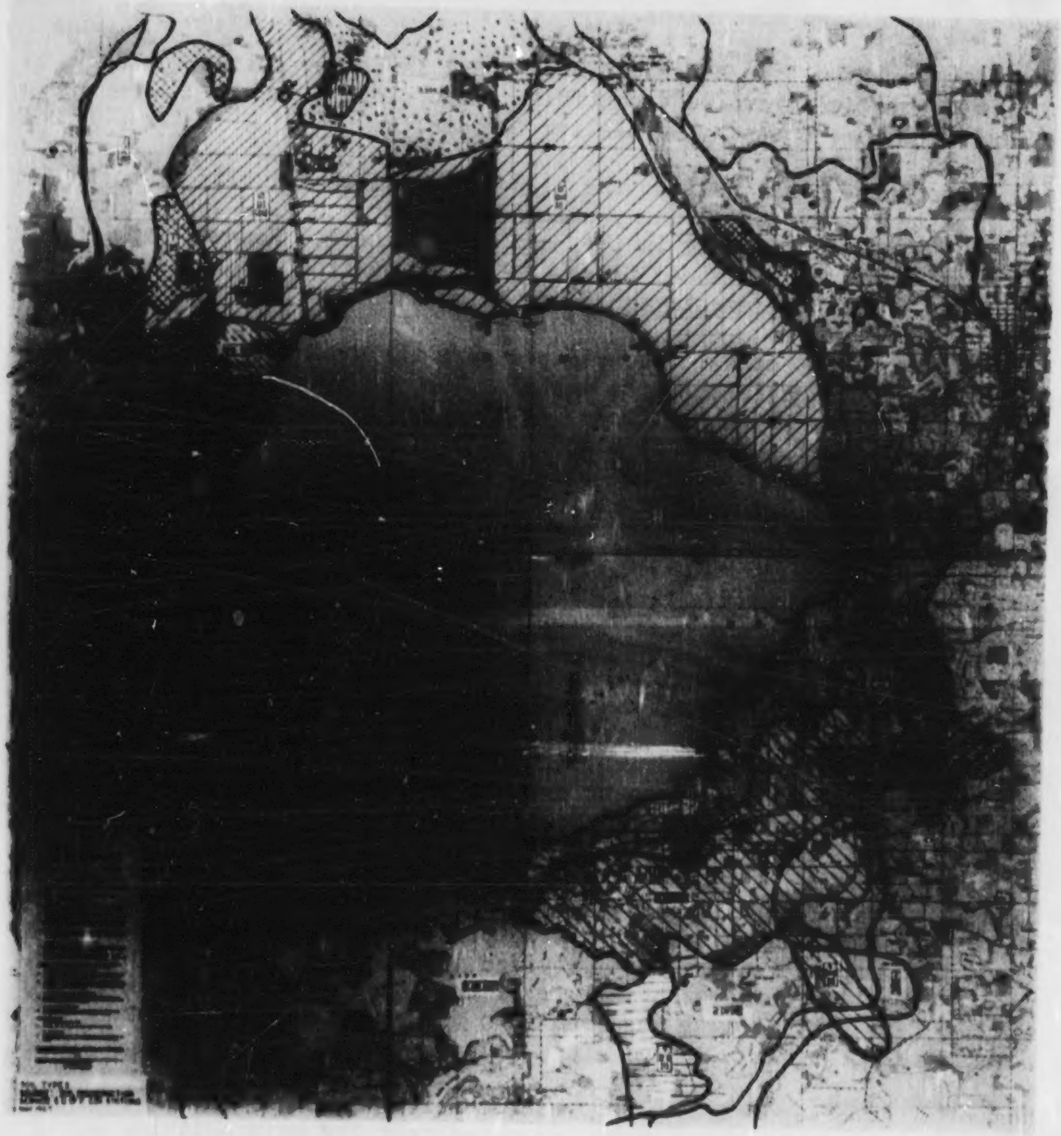


Figure 26. Reproduction of soil classification overlay map.

SCS offices, were tabulated for each of the various soil type regions shown in Figure 26. In this study, land use data were utilized as a guide for subjective estimation of lumped model parameters, such as Manning's surface roughness.

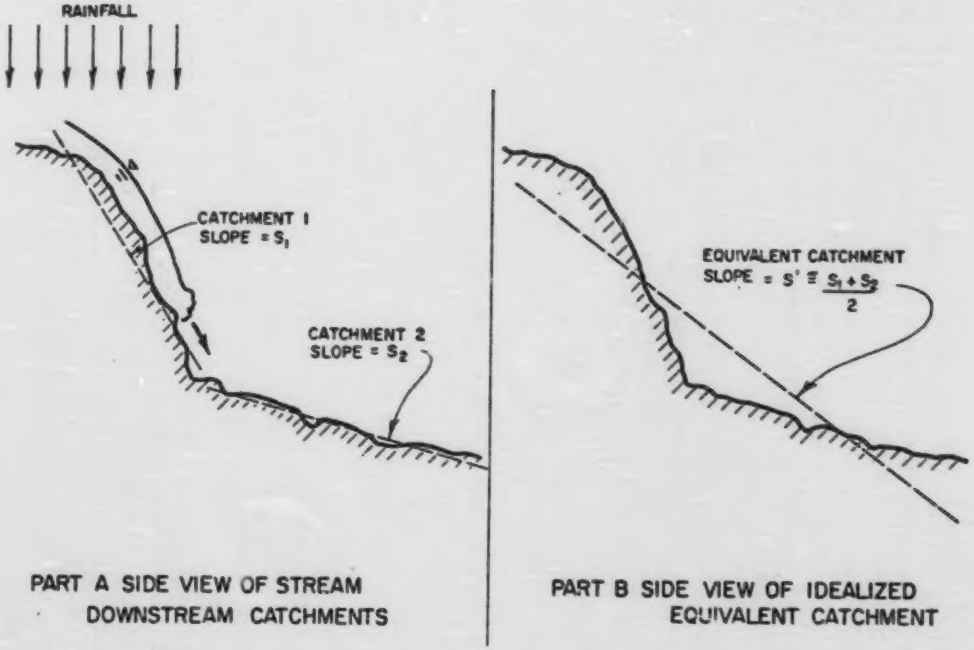
Layout of Catchments—
It then became necessary to consider the division of the area into catchments. For simplicity, it was assumed that the entire area was underlain by sandy soils, and thus soil type was excluded as a criterion for partitioning. Similarly, the scope of this particular investigation precluded the utilization of land use data in the division process. Therefore, the layout of catchments was carried out using only topographic criteria.

In the kinematic wave model used in this study, no provision is made for a given plane catchment receiving discharge from another upstream catchment. Thus, this situation, illustrated in Figure 27, part (a), could not be allowed to exist in the catchment layout. Instead, the alternative approach required by the present model would be to consider the upstream and downstream catchments as a single entity. This simplification is shown in part (b) of the same figure.

In general, the result of the simplification applied in (b) is decreased model accuracy due to the lumping of catchment slopes. However, in the sandy soils under consideration, the topography was such that the cascading case depicted in (a) was uncommon. In basins where cascading is widespread, it would be advisable to improve the capabilities of the kinematic wave model to handle this situation. In this regard, a review of recent studies at the Massachusetts Institute of Technology (Maddaus and Eagleson, 1969; Harley, Perkins and Eagleson, 1970), among other sources, should be useful.

In the sandy soils of the Lake Apopka basin, the predominant pattern is that of radial flow into local depressions. This situation is illustrated in Figure 28. Also shown in this figure is the division of the land surface into catchments. To avoid any lateral flows between catchments, their boundaries were drawn normal to contour lines. Ideally, the catchment slopes should be uniform, and their shape rectangular.

The catchment layout for the sandy soils area is provided in Figure 29. This figure consists of a reproduction of a plastic overlay map, similar to that used in delineating soil types (Figure 26). While most catchments drain into local depressions, others provide runoff to Lake Apopka. The latter catchments, of greater interest in this study, are depicted in Figure 30.


RAINFALL
CATCHMENT 1
SLOPE = S_1
CATCHMENT 2
SLOPE = S_2
EQUIVALENT CATCHMENT
SLOPE = $S' \cong \frac{S_1 + S_2}{2}$

PART A SIDE VIEW OF STREAM DOWNSTREAM CATCHMENTS

PART B SIDE VIEW OF IDEALIZED EQUIVALENT CATCHMENT

Figure 27. Illustration of the lumping of two successive catchments into one.

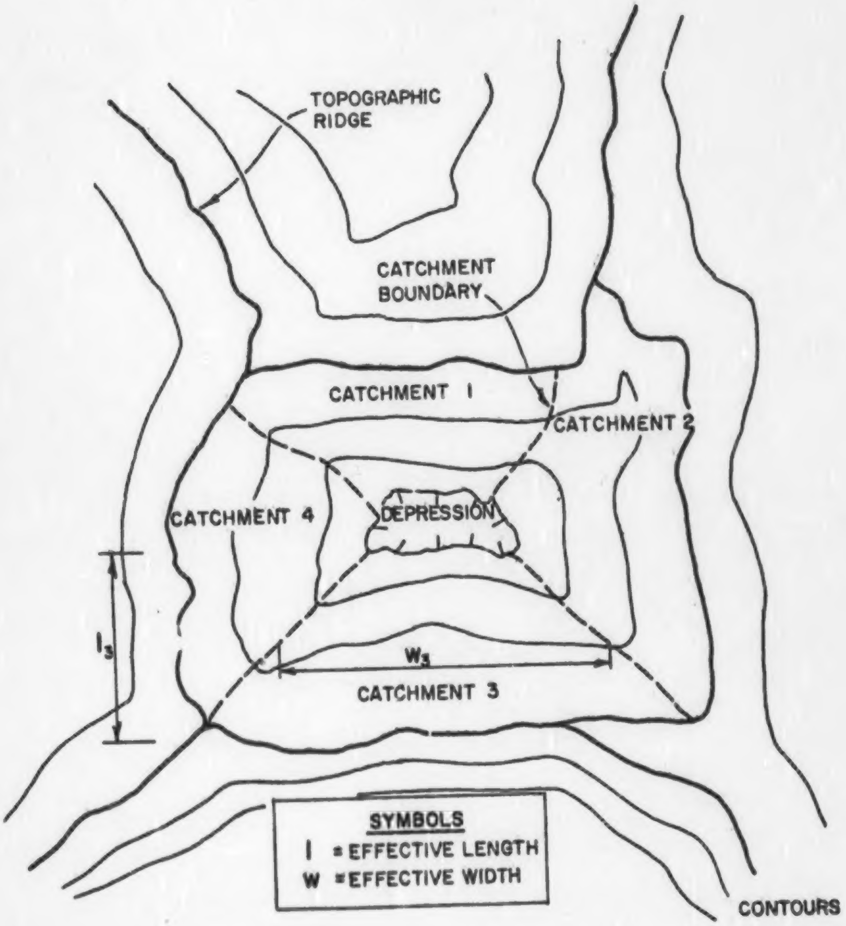

TOPOGRAPHIC RIDGE
CATCHMENT BOUNDARY
CATCHMENT 1
CATCHMENT 2
CATCHMENT 4
DEPRESSION
l_3
W_3
CATCHMENT 3
SYMBOLS
l = EFFECTIVE LENGTH
W = EFFECTIVE WIDTH
CONTOURS

Figure 28. Illustration of the topographic contours of the sandy soils and delineation of overland flow catchments.

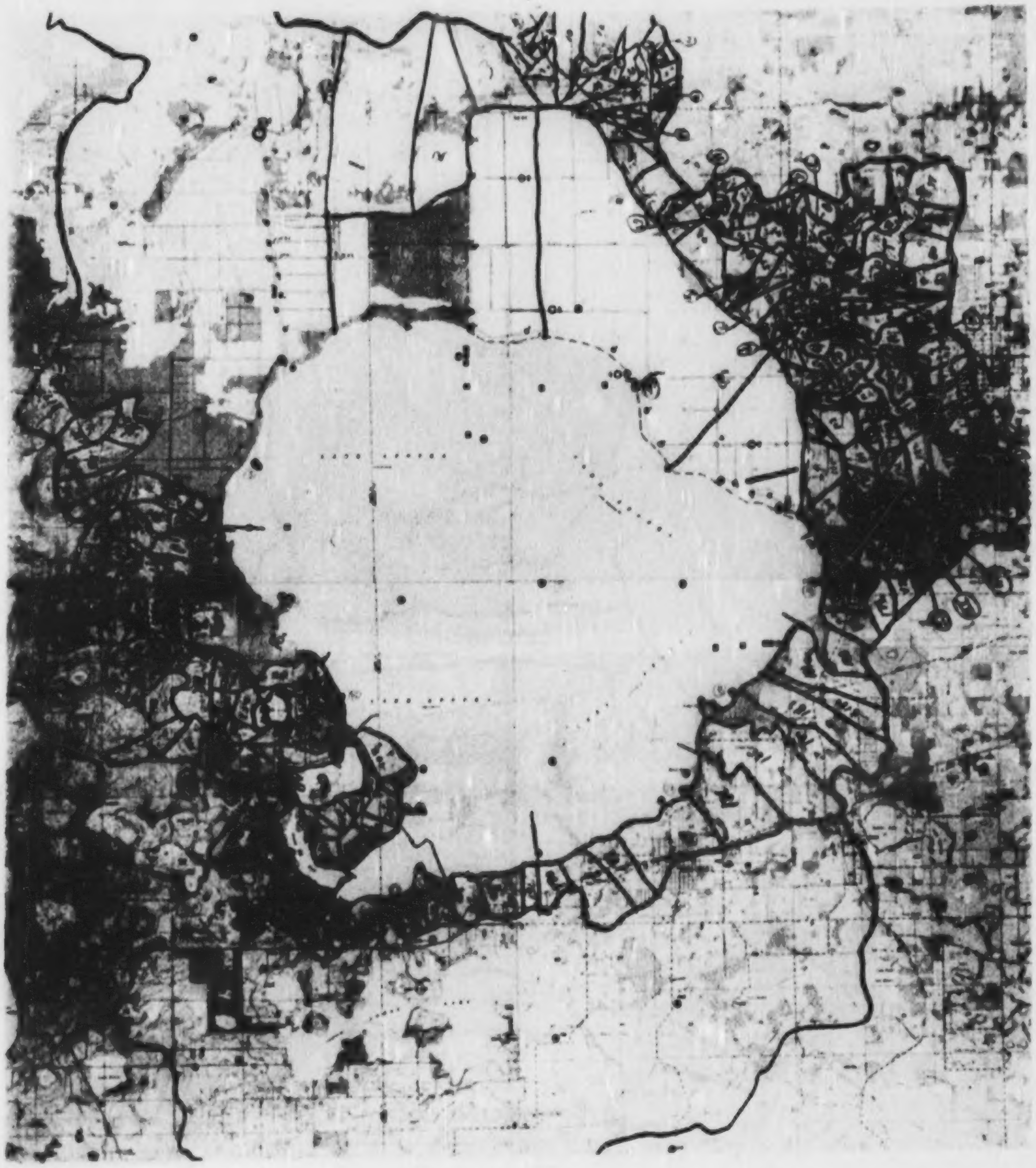


Figure 29. Reproduction of an overlay map showing the layout of overland flow catchments in the sandy soils.

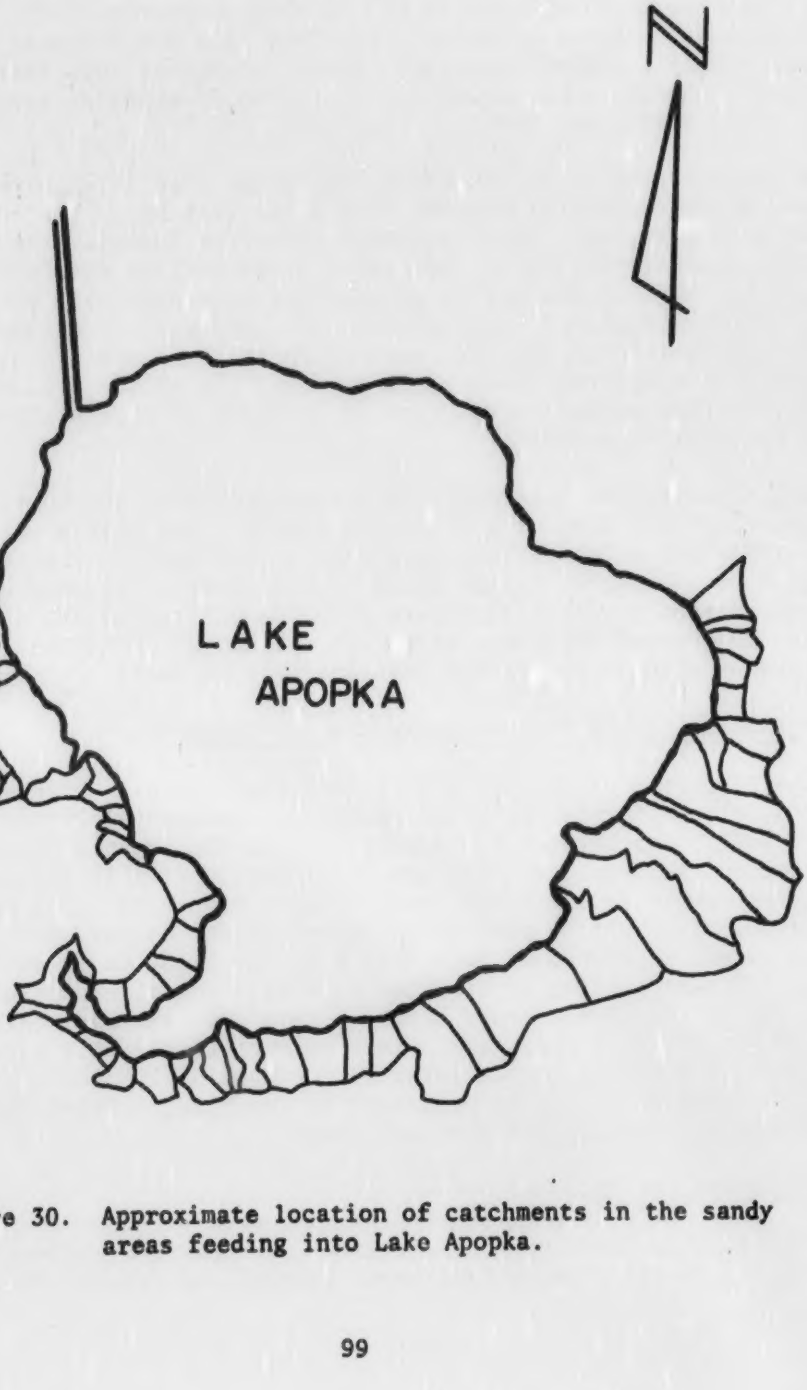

N
LAKE
APOPKA

Figure 30. Approximate location of catchments in the sandy areas feeding into Lake Apopka.

Model Parameters—

Regarding model parameters, the information contained in Figure 29 allowed the determination of the approximate length, width and slope of each catchment. The value of the Manning roughness coefficient ($n = 0.025$) was estimated subjectively from land use information, with the aid of a table (Henderson, 1966). Assuming turbulent flow conditions, the exponent parameter, m, in the formulation was set equal to 5/3 (Eagleson, 1970).

In the quality portion of the model, the grain size selected was that proposed by Gottschalk (1964) for fine sands (1/8 mm). The corresponding parameters for the DuBoys sediment transport formula were obtained from Einstein's (1964) work. Estimates of fertilizer nutrient content and loading rates in the citrus groves were made available by the East Central Florida Regional Planning Council. The quality assumptions and calculations involving nitrogen and phosphorous are discussed in Appendix E. References on nutrient availability at the ground surface originating from animal wastes (not of interest in this study area) are provided in Appendix F.

Finally, the overland flow model receives input from the unsaturated zone model, in the form of infiltration rates. The spatial variability of the thickness of the unsaturated zone in the sandy soils was shown in Figure 24. However, partitioning of the unsaturated zone on this basis was deemed unwarranted from a model demonstration standpoint. Instead, an average thickness value was estimated. Additional details are given in discussions of the unsaturated zone model.

Runoff Portion of the Stormwater Management Model

The runoff portion of the Stormwater Management Model, which was originally developed for use in urban basins (Environmental Protection Agency, 1971), was adapted for application to the organic (muck) soils area north of Lake Apopka. The general location of this area, comprising approximately 18,000 acres, was shown in Figure 20. Due to the high permeability of the muck soils (Harrison and Weaver, 1958) and the widespread existence of mole drains in the area, it is unlikely that significant ponding or overland flow will occur, except under rainstorms of very high intensitites. Therefore, the application of the stormwater runoff model was primarily for illustrative purposes, especially with regard to the interfacing aspects with the receiving model. At this point, it is pertinent to interject a brief discussion of the general hydrology of the muck farms.

Hydrologic Inflows and Outflows—

From a hydrologic budgeting standpoint, the muck farms area is much more complex than the sandy soils region. The various surface inflows and outflows (aside from rainfall and evaporation) for the muck farms are illustrated in Figure 31 for the Zellwood Drainage District. The least significant of the factors shown is considered to be the overland flow from the higher, sandy soils. On the other hand, the pumpage rates into Lake Apopka are known to be high, especially following large rainstorms. Unfortunately, these pumpage records, made available through the East Central Florida Regional Planning council (ECFRPC), constitute rough estimates based on approximate duration of pumpage and head differential. Furthermore, the rates are given as district totals, and are not broken down by individual pumps.

In dry periods, irrigation water for the muck farms is obtained from Lake Apopka through several flap valves located along the earthen dike. The approximate number and diameter of these inlets, shown also in Figure 31, were obtained from Zellwood Drainage District records. However, no records are kept on the operation of the valves. Rough calculations indicate that at any time in which valves are open, the resulting flows could be significant.

In the subsurface water category, the inflows and outflows for the muck farms area are also not well known. Section EE', shown in Figure 31, can be examined to illustrate the groundwater regime. A lateral view of this section is provided in Figure 32. Considering first the left-hand portion of the section, it becomes apparent that seepage could occur from Lake Apopka to the muck farms through the earthen dike, although the amount is uncertain. Also, groundwater flow originating in the sandy soils could enter the muck farms. The extent of the latter contribution would depend upon the actual water table elevation in the sandy areas and the local permeability. Additional discussion on this point is provided in the sub-section on groundwater.

It follows from the above comments on the nature of the surface and subsurface flows that the system at hand is indeterminate. At best, only rough estimates or ranges of inflows and outflows could be used in budgeting attempts for the general area (Heaney, Perez and Fox, 1972). This hydrologic uncertainty affected the calculations for runoff and other phenomena.

Layout of Runoff Catchments-

The purpose of the runoff formulation is to compute the flows and nutrient fluxes into the drainage canals. The flow and quality processes in the canals are handled by the receiving model. A diagram of an isolated portion of the drainage system under study is provided in Figure 33. Part (a) of this figure constitutes a plan view of the isolated unit.

Indicated therein are the mole drains, which are spaced approximately 20 feet (6 m) apart. A lateral view of the system is shown in part (b).

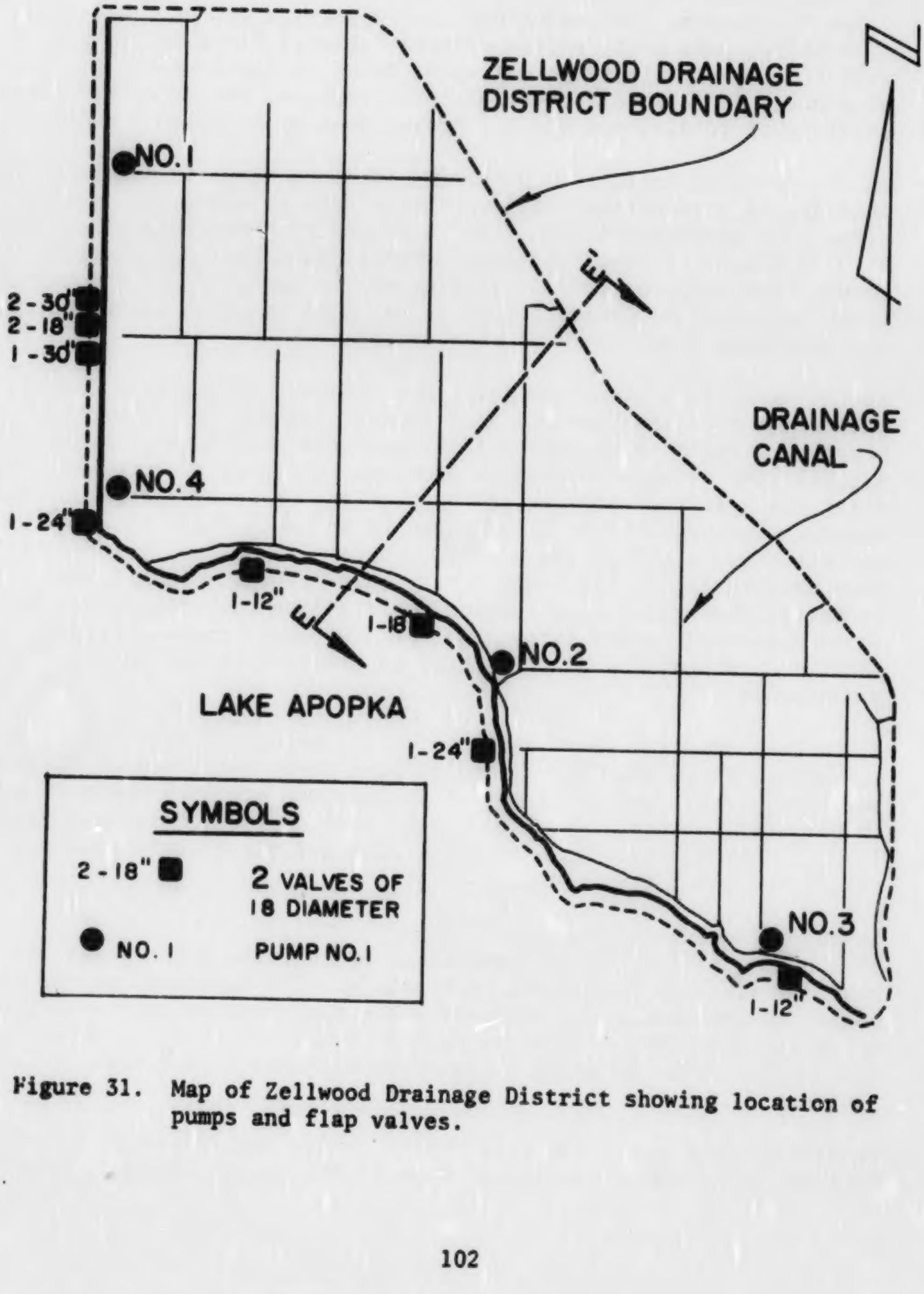

ZELLWOOD DRAINAGE DISTRICT BOUNDARY
N
NO. 1
2-30"
2-18"
1-30"
E
E'
DRAINAGE CANAL
NO. 4
1-24"
1-12"
1-18
NO. 2
LAKE APOPKA
1-24"
SYMBOLS
2-18" ■ 2 VALVES OF 18 DIAMETER
● NO. 1 PUMP NO. 1
NO. 3
1-12"

Figure 31. Map of Zellwood Drainage District showing location of pumps and flap valves.

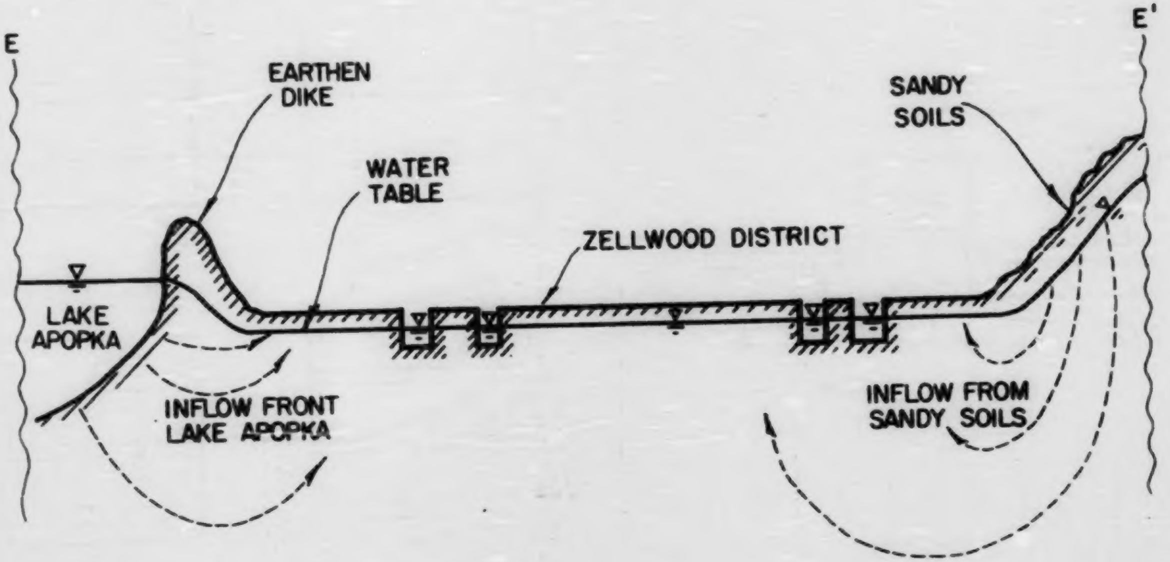
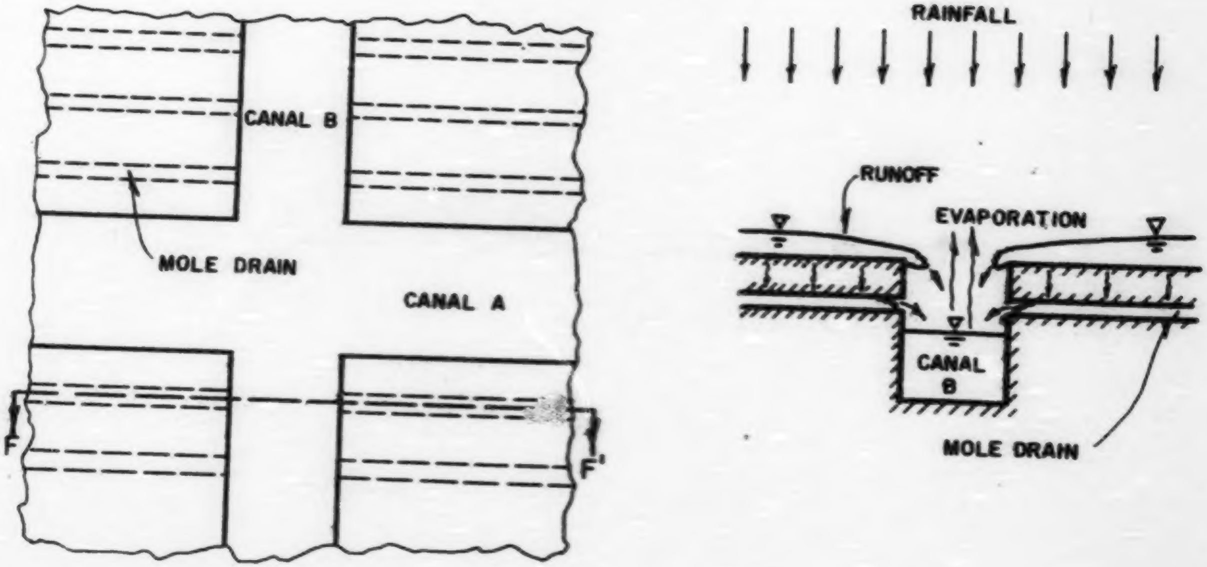

E
E'
EARTHEN DIKE
WATER TABLE
ZELLWOOD DISTRICT
SANDY SOILS
LAKE APOPKA
INFLOW FRONT LAKE APOPKA
INFLOW FROM SANDY SOILS

Figure 32. Simplified lateral view of vertical section EE' (Figure 31) in Zellwood Drainage District.


CANAL B
MOLE DRAIN
CANAL A
F
F'
RAINFALL
RUNOFF
EVAPORATION
CANAL B
MOLE DRAIN

PART(A) PLAN VIEW

PART(B) LATERAL VIEW OF FF'

Figure 33. Plan and lateral views of an isolated portion of the drainage system in the muck farms.

The receiving model applied to the canals utilizes flow and quality inputs from two sources: (1) overland flow (runoff model) and (2) mole drains (unsaturated zone model).

Considering drainage aspects from a broader standpoint, the muck farms are effectively divided into two systems of roughly equal acreage: the Zellwood Drainage District (shown in Figure 31) and the Duda Drainage District. Figure 34 is a reproduction of a working map of the former, indicating the numbers used for the various catchments and receiving junctions. A similar map is provided for the Duda area, in Figure 35. In the runoff simulation, these two districts were considered as independent entities, and calculations were conducted separately.

Model Parameters—
In the flow computations, two main parameters were required: land slope and Manning's roughness (n). Due to the flat nature of the muck farms surface, the former could not be estimated from topographic maps. Instead, an arbitrary value of 10^{-4} ft/ft was selected for all catchments in Zellwood and Duda. The value of the roughness coefficient used was $n = 0.04$.

An important parameter required in the quality portion of the model was the grain size of the muck soil. In the absence of data, the assumption was made that, in suspension, muck is somewhat akin to silt. Accordingly, a grain size of 10^{-2} mm was used. Other corresponding sediment load parameters were estimated by extrapolation of the tables given by Einstein (1964). Additional information on the suspended solids calculations are given in Appendix A.

The nutrient contents of the suspended solids loads, computed above, were estimated with the aid of fertilizer data provided by the East Central Florida Regional Planning Council (ECFRPC). Specifically, data on nutrient content in fertilizer, loading rates and crop types were obtained for each major farm. A map showing the subdivision of the Zellwood district into farms is provided in Figure 36. Yearly average nutrient loading rates were computed for the entire muck farms area by Heaney, Perez and Fox (1972). The estimation of nutrient contents in suspended solids using the above yearly rates is explained in Appendix E.

Receiving Water Model

In this study, the receiving formulation was utilized in a stepwise fashion. First, it was applied separately to the Zellwood and Duda districts in the muck farms area. Subsequently, the output from these two programs was used as input to the receiving program for Lake Apopka.

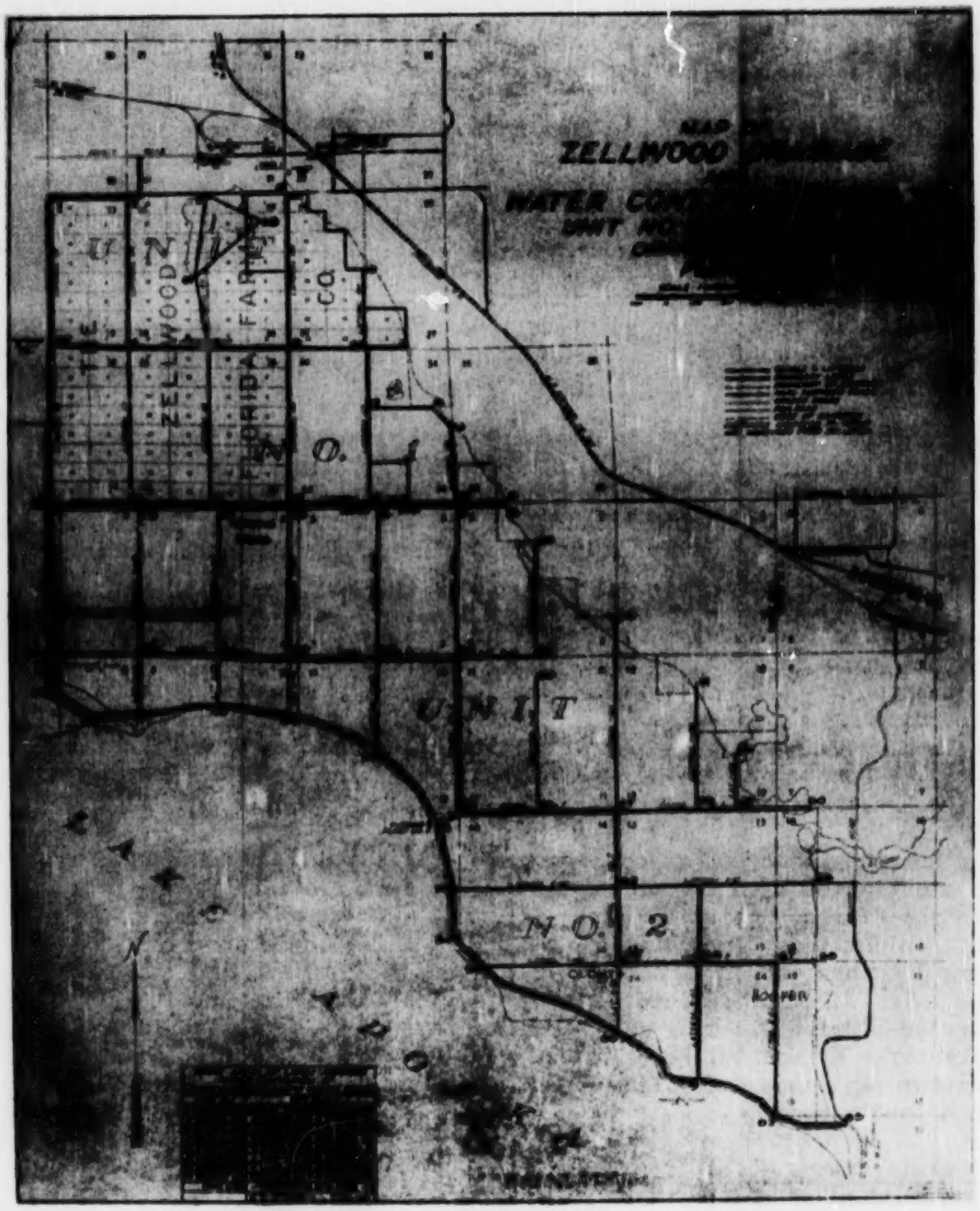

ZELLWOOD
WATER CON
THE ZELLWOOD FLORIDA FARMS CO.
UN NO.
UNIT NO. 2
N

Figure 34. Reproduction of runoff map for the Zellwood Drainage District in the muck farms.

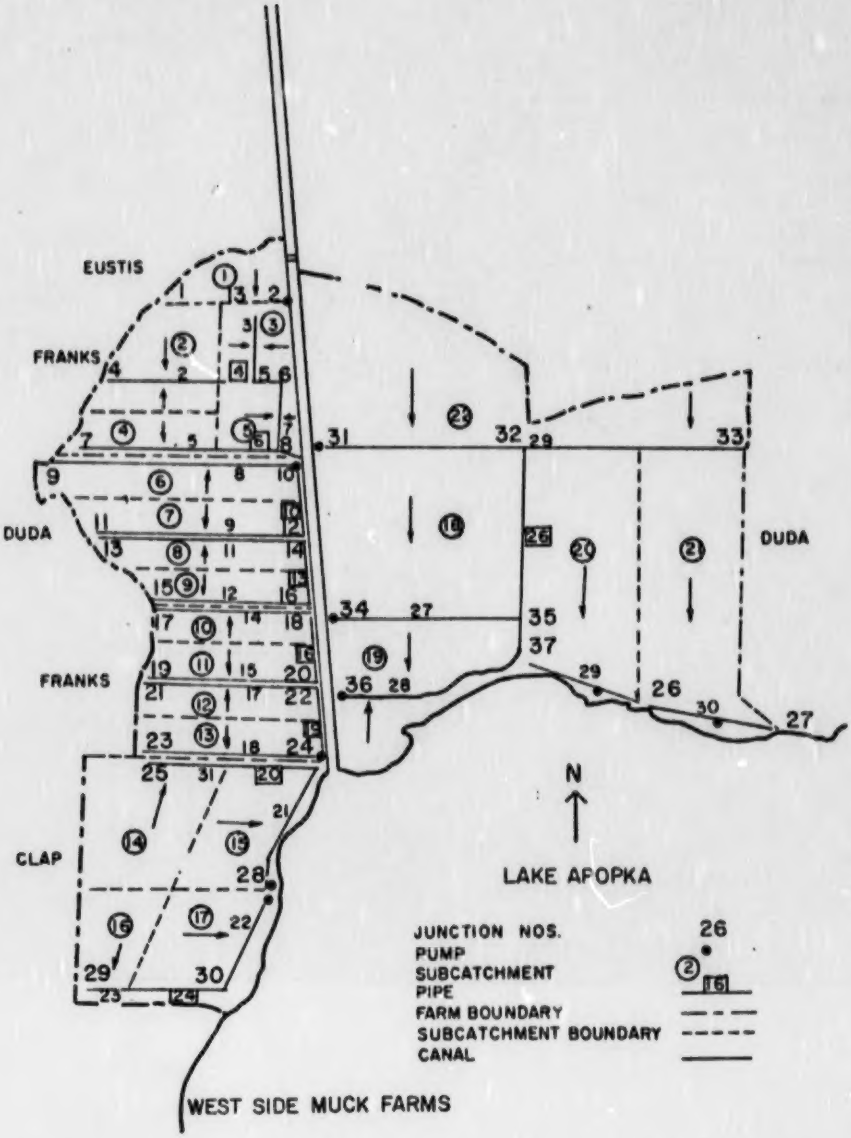

EUSTIS
FRANKS
DUDA
FRANKS
CLAP
DUDA
N
LAKE APOPKA
JUNCTION NOS.
PUMP
SUBCATCHMENT
PIPE
FARM BOUNDARY
SUBCATCHMENT BOUNDARY
CANAL
WEST SIDE MUCK FARMS

Figure 35. Runoff map for the Duda Drainage District in the muck farms.

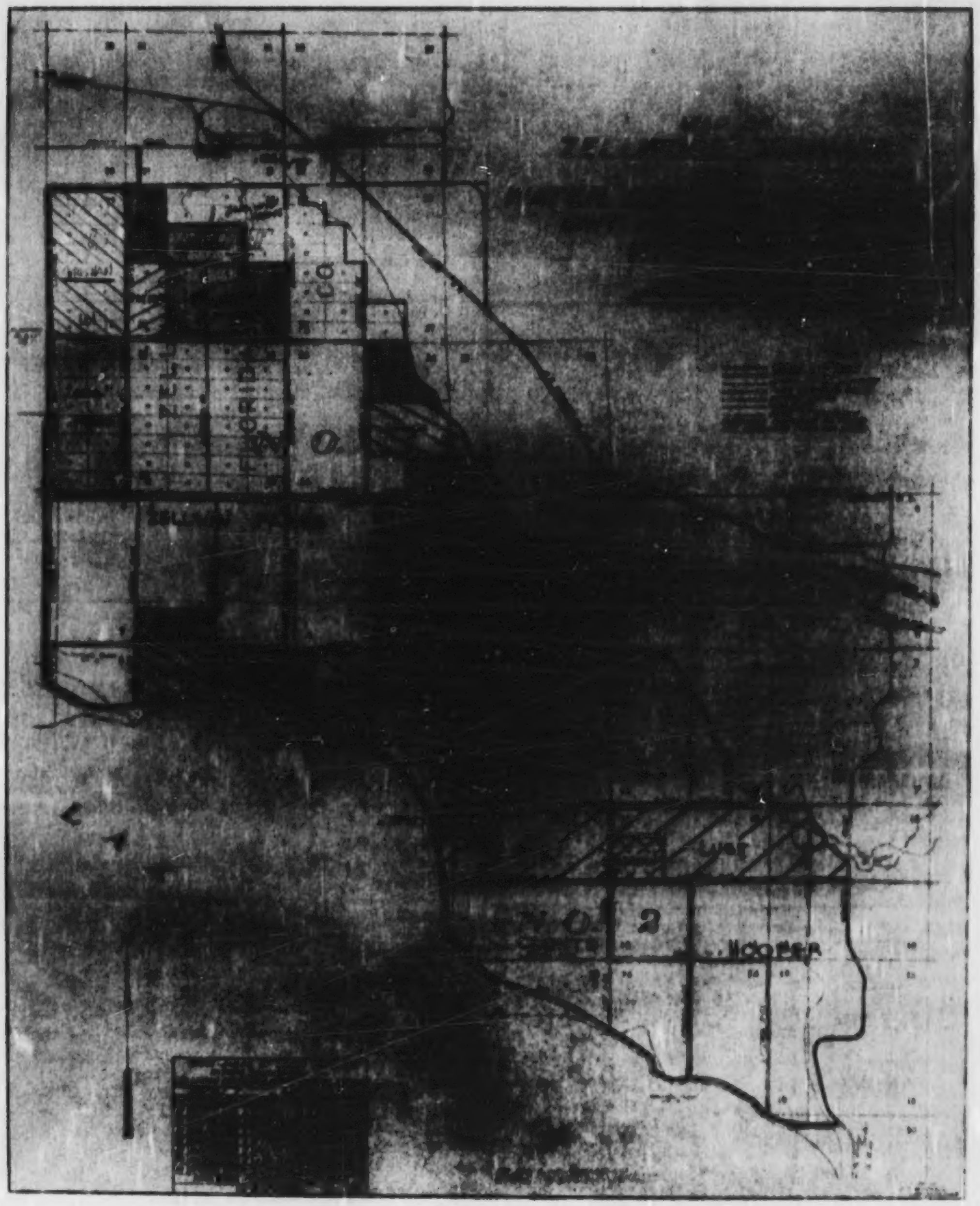


Figure 36. Reproduction of map showing the different farms within the Zellwood Drainage District.

Application to Drainage Canals—

To consider the different variables and parameters used in the model, it is worthwhile to isolate a small portion of a hypothetical canal system for closer examination. This isolation process is carried out in Figure 37. Shown therein are the boundaries of a typical receiving unit, known as a junction. Associated with each junction are its bottom elevation and water surface area. These parameters were estimated from canal geometry data obtained by the East Central Florida Regional Planning Council (ECFRPC) from personnel associated with drainage operations. Most of the canal geometry data were quite rough approximations, since no accurate records exist and the canals are frequently dredged. However, supplementary field measurements would have been beyond the scope of this study.

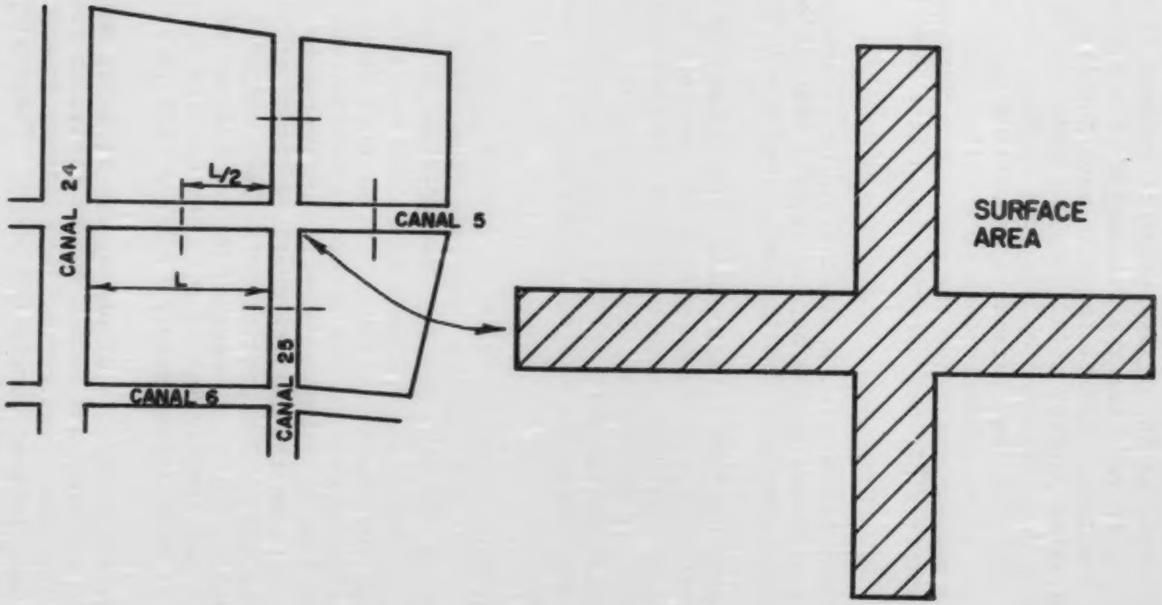
In addition to these parameters, an initial value of water surface elevation must be provided at the beginning of a simulation run. The Manning coefficient value used for the canals was $n = 0.025$.

With regard to water quality calculations, the absence of data dictated that a value of zero be specified for source/sink and decay rates. Likewise, the initial nitrogen and phosphorous concentrations were set at zero for convenience. The zero values above were not used in all computer runs. For instance, concentration data collected by the Orange County Pollution Control Department were sometimes used as initial values.

From the previous discussion of the runoff model (Figure 33), it may be recalled that a channel junction receives flow and quality input from both runoff and the mole drains. In addition to these two sources shown in Figure 33, provision was made to include vertical groundwater flow through the channel bottom. In the muck farms, it is thought that this flow occurs in the upward direction, and its magnitude was obtained from hydrologic budgeting estimates by Heaney, Perez and Fox (1972). Data on the quality characteristics of this upflowing water are not available. Evaporation rates were computed from pan evaporation rates for the U. S. Weather Bureau station at Lisbon, Florida. Using a pan coefficient of 0.78 (Heaney and Huber, 1971), the computed rates were approximately 50 in/yr (127 cm/yr).

Turing to broader scale aspects of usage, the receving model was applied separately to the Zellwood and Duda drainage districts (see Figures 34 and 35). In the Duda area, certain simplifying assumptions were made on the linkages between canals and pumps. These simplifications are illustrated in Figure 38.

The flow portion of the receving model involves iterative calculations to determine the stage at the various junctions, in response to pumpage and other hydrologic inputs to the channels. Since the pumping figures



CANAL 24
L/2
L
CANAL 5
CANAL 25
CANAL 6
SURFACE AREA

Figure 37. Illustration of a typical receiving water model junction in the muck farm canals.

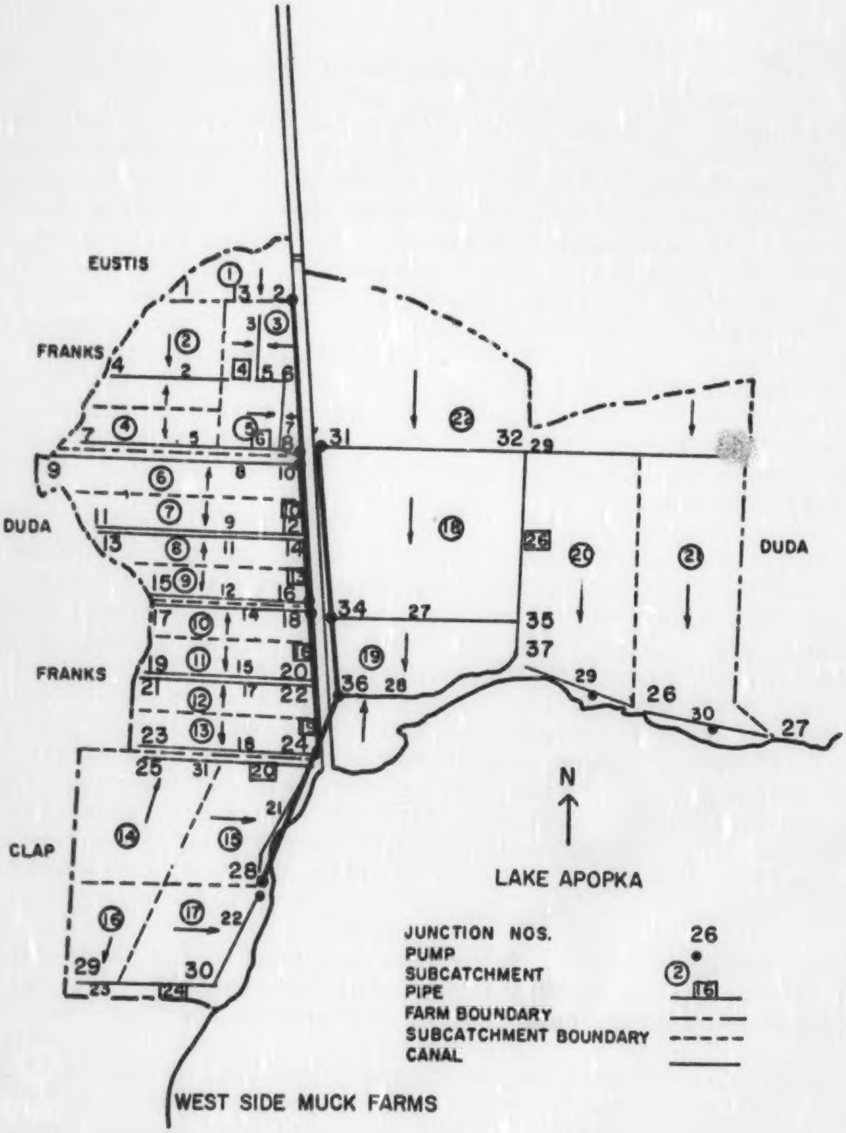

EUSTIS
FRANKS
DUDA
FRANKS
CLAP
DUDA
LAKE APOPKA
N
WEST SIDE MUCK FARMS
JUNCTION NOS. 26
PUMP
SUBCATCHMENT ②
PIPE 16
FARM BOUNDARY
SUBCATCHMENT BOUNDARY
CANAL

Figure 38. Map of the Duda Drainage District showing simplified connections for the receiving water model.

available for both Zellwood and Duda were not broken down by individual pumps, arbitrary weights (percentages of total pumpage) were assigned to the pumps. For instance, pump numbers 1 through 4 in the Zellwood District were given weights of 0.20, 0.35, 0.25, and 0.20, respectively.

Application to Lake Apopka—
While the surface inflows from the muck farms occur as point sources, any overland flows from the sandy areas (see Figure 30) consist of distributed input. Data for other inflows and outflows (see Figure 21) are available from other sources. Preliminary measurements of Gourd Neck Spring flow by the U.S.G.S., taken during low piezometric conditions in the Floridan Aquifer, indicated an approximate value of 18 MGD (0.79 m^3/sec). It was assumed herein that the spring flow varied linearly with the head differential between the aquifer and the lake, and thus a yearly average flow value of 22 MGD (0.96 m^3/sec) was obtained. The average annual outflow from the Winter Garden canal was estimated by the East Central Florida Regional Planning Council (ECFRPC) to be 2.1 MGD (0.092 m^3/sec). Quality data for this canal are available from the Orange County Pollution Control Department. Daily flows at the Apopka-Beauclair Canal were tabulated by the ECFRPC. Also, evaporation rates were estimated at 50 inches per year (127 cm/yr) as discussed previously.

The receiving model has the capability of incorporating subsurface inputs in addition to the surface flows discussed above. However, in the case of Lake Apopka the former were neglected. As pointed out by Anderson (1971), lateral seepage from the surrounding sandy areas to the lake probably accounts for only a small percentage of total lake inflow. Also, a comparison of the mean lake stage, 67 ft (20 m), M.S.L. to the piezometric map of the Floridan Aquifer (see Figure 22) indicates that upward flow occurs in the southwestern half of the lake, and downward flow of possibly the same order of magnitude takes place in the northeastern portion. Although Anderson's report implies that these two flows are not offsetting, a simplifying assumption of no vertical flow throughout the lake was made for model demonstration purposes.

No data are available for the flows from the lake to the farms through the flap valves, or for seepage through the earthen dike. For this reason, these two factors could not be included in the analysis.

The development of a link-node, or channel-junction, system for Lake Apopka was carried out by first considering the location of the various surface inflows and outflows. It was concluded that boundary nodes should be located at approximately equally spaced intervals along the periphery of the lake, and as close as possible to the inflow/outflow locations. Next, the positioning of the interior nodes was considered in the light of prior computational efforts in the Florida Everglades by Heaney and Huber (1971). Programming experience gained in that study indicated the desirability of designing a link-node structure in which: (1) links should form sets of approximately equilateral triangles and (2) triangles should have about the same size, Another criterion for locating nodes was proximity to the Orange County Pollution Control Department sampling stations. The resulting link-node system developed using these criteria is shown in Figure 39. The flow and quality inputs from the catchments in the sandy areas were assigned as point sources to the nearest boundary node.

The geometrical data required for a typical junction consist of bottom elevation and water surface area. For the purposes of this study, the lake bottom was assumed to be flat, although contour maps of the bottom surface (Sheffield and Kuhrt, 1969) indicate some areal variability. The principle for delineating the surface area assigned to each junction is analogous to that used in determining Thiessen weights in rainfall calculations (Linsley and Franzini, 1964).

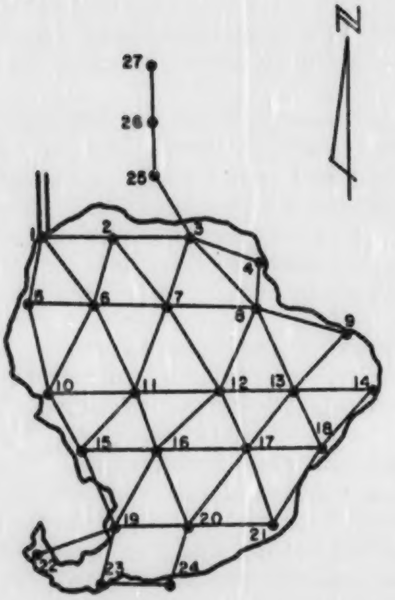
Quality computations in the lake receiving model require data on source/sink and decay rates, in addition to initial pollutant concentrations. In general, the same guidelines that applied to the drainage canals were used in the lake. In their 1968 study of Lake Apopka, Schneider and Little pointed out the importance of nutrient cycling between water and sediments, and mentioned the work of Kuznetsov (1968) in the Soviet Union. A review of Kuznetsov's paper indicated that little attention was devoted to phosphorous, and the applicability of his nitrogen rates to Lake Apopka was considered uncertain. However, this and other papers should provide insight into the methodology for obtaining these needed source/sink rates.

Unsaturated Zone Model

General Description—

Boundary conditions— The main boundary conditions involved in this model are: rainfall, evaporation and net recharge. These parameters are illustrated in Figure 40. In the Lake Apopka basin, rainfall data were available from the U. S. Weather Bureau stations at Clermont and Lisbon. Pan evaporation measurements were available at the latter station. Also, daily rainfall records for various stations within the muck farms area were provided.

Regarding the usage of these data, it might be first pointed out that, due to the high infiltrative capacity of the soils in the basin, the utilization of average daily (or even hourly) rainfall rates would have resulted in the prediction of no overland flow. Thus, synthetic rainstorms were constructed somewhat arbitrarily from the existing data, in which the intensity was expressed as an exponentially


N
27
26
25
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

INPUTS AT JUNCTION

JUNCTION	FLOW, ft^3/sec	N-FLUX, lb/day	P-FLUX, lb/day
1	500	21,600	810
2	200	21,600	860
4	300	16,200	650
5	200	9,700	433
9	200	—	—
25	200	9,700	433
27	200	3,230	108

Figure 39. Location of various junctions for the receiving water model application in Lake Apopka. Also shown are inputs for the lake simulation.

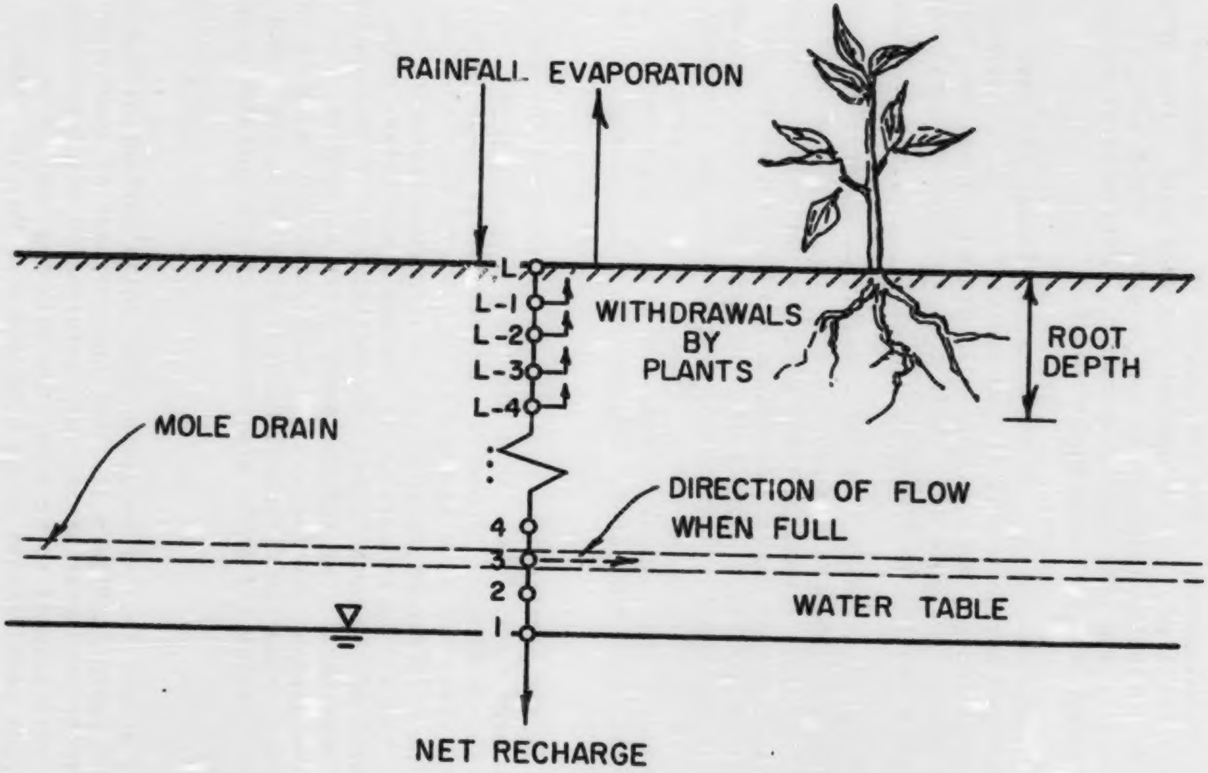

RAINFALL
EVAPORATION
WITHDRAWALS BY PLANTS
ROOT DEPTH
L
L-1
L-2
L-3
L-4
MOLE DRAIN
DIRECTION OF FLOW WHEN FULL
4
3
2
1
WATER TABLE
NET RECHARGE

Figure 40. Cross-sectional view of the unsaturated zone, showing boundary conditions and other model features.

decaying function of storm duration. This relationship is considered to be approximately valid for thunderstorms (Eagleson, 1970). In future studies, it would be desirable to obtain better rainfall information, since it is an important factor in determining so-called first flush effects in overland flow quality.

In evaporation calculations, a pan coefficient of 0.78 (Heaney and Huber, 1971) was utilized. The assumption was made that, since soils in the basin are irrigated (especially muck), water would always be available to satisfy the potential evaporation. Estimates of recharge rates were obtained from the groundwater model.

Additional features— In addition to the external flows, the unsaturated zone model developed herein considers two features: (1) withdrawals of water by plants and (2) outflows via mole drains. These two features are also shown in Figure 40. Their corresponding mathematical formulations are presented in Appendix E.

Areal partitioning criteria— A simplistic partitioning process for the unsaturated zone was conducted to promote the homogeneity of model parameters within each region. Accordingly, the criteria considered for this division process were those parameters which were thought to vary areally in the basin. Since lack of data precluded consideration of areal variations in rainfall and evaporation, the remaining factors were: (1) net recharge rate, (2) soil type, (3) crop type, and (4) existence of mole drains. Items (3) and (4) were considered homogeneous within each soil type, thus leaving only (1) and (2) as effective criteria.

The next step in the partitioning process was to consider the variability of recharge conditions within the two major soil types, muck and sand. An examination of Figure 24 indicated that, while groundwater flow conditions might be assumed to be homogeneous within the muck farms, wide differences could exist between conditions in the sandy soils in the southwest portion of the basin and those in the sandy soils north of the muck farms. Accordingly, three unsaturated zone programs were used: two for the sandy soils and one for the muck farms. The distinctive features of each partition, such as soil mositure-pressure-conductivity relationships, plant root depth and location of mole drains (if any), are imbedded in its corresponding computer program.

Sandy Soils—

Description of areas— The two separate sandy soils regions discussed above are shown again in Figure 41. For the purposes of this study, the soil hydraulic characteristics, crop information and fertilizer loading rates were assumed to be equal for both regions. Also, both unsaturated zones were assumed to be homogeneous. However, their geometrical characteristics and recharge rates differ.

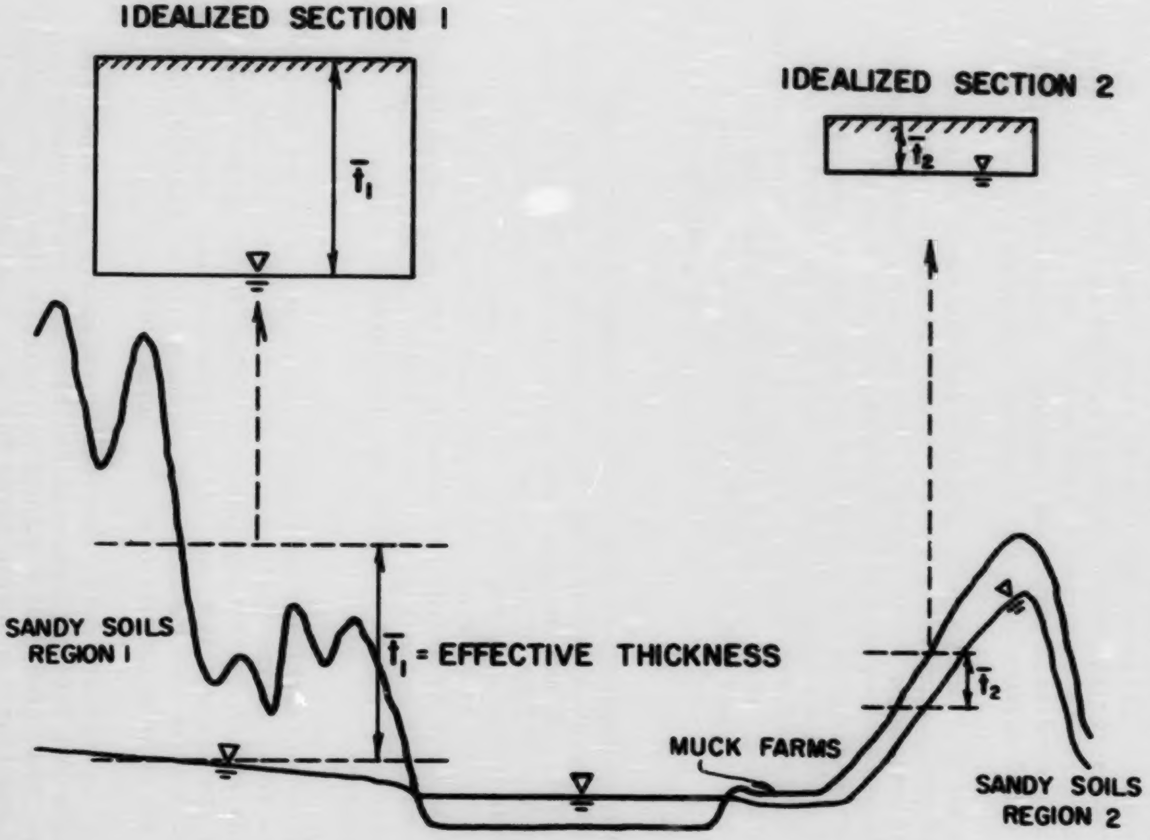

IDEALIZED SECTION I
$\bar{t}_1$
IDEALIZED SECTION 2
$\bar{t}_2$
SANDY SOILS
REGION I
$\bar{t}_1$ = EFFECTIVE THICKNESS
MUCK FARMS
$\bar{t}_2$
SANDY SOILS
REGION 2

Figure 41. Partial view of cross-section AA' (Figure 23), illustrating the idealization of the unsaturated zone geometry.

To conform with geometrical assumptions inherent in the model, the ground and water table surfaces were redrawn in Figure 41 as parallel, horizontal lines. The resulting distortion, especially apparent in the northeastern region, is due in a large measure to the vertical scale exaggeration in the figure. Thus, horizontal moisture gradients are likely to be of little actual significance. The horizontal linearization process for the water table is carried out only for internal calculations in the unsaturated zone model. Prior to the transfer of data to the groundwater model, any computed change in water table elevation is added uniformly to the original irregular surface.

Flow parameters— Included in both programs for the sandy areas are function subprograms containing the algebraic expressions for the following soil hydraulic relationships: (1) moisture versus pressure head, (2) conductivity versus pressure head, (3) slope of the moisture versus pressure head curve, as a function of the latter and (4) pressure head versus moisture content. Using data for Florida sandy soils (Stewart, Powell and Hammond, 1963), it was possible to construct a curve for item (4), which is shown in Figure 42. The value of saturated hydraulic conductivity (permeability) assumed herein was 3 inches per hour (7.6 cm/hr). A plot of item (2) is provided in Appendix E.

Regarding evapo-transpiration from citrus orchards, a yearly mean rate of 0.12 in/day (0.3 cm/day) was estimated from studies by Hashemi and Gerber (1967). It was assumed that transpiration from the plants accounted for four-fifths of this total water loss, the remaining portion being evaporation from the soil. The root depth of citrus was estimated at 5 ft (1.5 m) from a table provided by Eagleson (1970). The water uptake rate by citrus was assumed to vary with depth in the following manner: 75 percent of the total demand is removed from the upper one-fourth of the root zone and the remaining 25 percent from the lower three-fourths.

Quality parameters— Fertilizer application rates and nutrient contents for the citrus areas in the basin were made available by the East Central Florida Regional Planning Council. Other interspersed land uses exist in the sandy soils, but for convenience these loading rates were prorated on the basis of citrus versus total acreage, and then assumed to apply uniformly over the sandy soils.

Due to lack of appropriate data, the setting of source and sink terms for both nitrate and total phosphorous was based on rough assumptions. It would appear that sandy soils should not release significant amounts of nutrients, and thus the source terms for both substances were set at zero. The estimation of sink rates was more elusive. Since Schneider and Little (1968) reported high N and P in their shallow sampling wells in the citrus areas, trial values of zero for these two

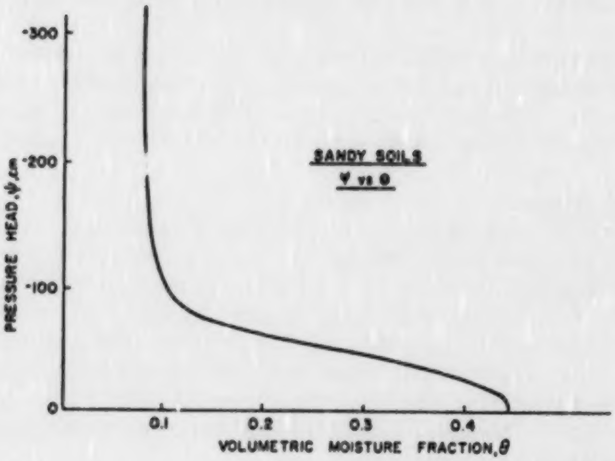


Figure 42. Estimated pressure head versus volumetric moisture fraction curve for sandy soils.

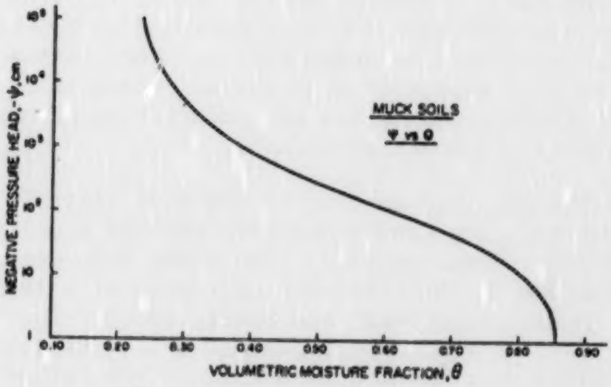


Figure 43. Estimated pressure head versus volumetric moisture fraction curve for muck soils.

substances were used. Also, little information was available on the nutrient uptake rates by citrus crops. The assumption was made that the ratios of yearly nitrate and phosphate uptake to the corresponding amounts applied in fertilizer were the same as those obtained for the muck farms. The corresponding calculations are shown in Appendix E.

The dispersion coefficients at the various nodes, which depend upon the corresponding velocities, were computed using the Hoopes and Harleman (1965) formula discussed earlier. The original constants used therein for sand were utilized in this study.

Muck Farms—

Description of area— The surface of the muck farms is very flat. Likewise, the water table is maintained at approximately 2 feet (0.6 m) below ground level with the aid of mole drains and drainage canals. Except for these discontinuities in the soil medium, the system is compatible with the assumption of one-dimensional, vertical flow. Also, the horizontal cross-sectional area occupied by the drainage canals is only a small percentage of the total muck farms area. The behavior of the mole drains was incorporated into the model (see Appendix E).

Flow parameters— The unsaturated flow model contains function subprograms for all the soil hydraulic relationships listed previously in the sandy soils section. The pressure head versus moisture curve used (Weaver and Speir, 1960) is shown in Figure 43. The conductivity versus pressure head curve is provided in Appendix E. As in the sandy soils, this curve is hypothetical. Very little information is available on this aspect of muck soils. Based on studies by Harrison and Weaver (1958), the saturated conductivity of muck was assumed to be 7.5 inches per hour (19 cm/hr).

Since the moisture content of the muck soils is carefully controlled, initial moisture conditions were assumed equal to field capacity at every node in the profile. The water requirements of the vegetable crops grown in the area were estimated at 0.15 inches per day (0.38 cm/day) (Harrison, Stewart and Speir, 1960). The root depth for all these crops was assumed to be 1 foot (0.3 m). Calculations for mole drains were based on a formula developed in the Netherlands (Weaver and Speir, 1960) and are explained in Appendix E.

Quality parameters— The initial nitrate and total inorganic phosphorous concentrations at the top node of the soil profile were estimated from the results of a nutrient budget study conducted by Heaney, Perez and Fox (1972). The corresponding calculations, which were based on assumptions about nutrient movement and availability, are briefly discussed in Appendix E. Plant nutrient uptake rates were estimated from data contained in this nutrient budget study, such as crop harvest weights, N and P contents and duration of growing seasons. The calculation of these uptake rates is also discussed in Appendix E.

Although fertilizers provide nutrient input to the percolating water, it appears that the major source of nutrients to this water is the muck soil itself. The water quality data collected by Hortenstine and Forbes (1971) for both fertilized and nonfertilized plots in the muck farms area provide support to this theory. Unfortunately, the driving forces and mechanisms affecting the release of these nutrients are not well understood. Muck of the research work on muck soils has dealt with consolidation aspects (Stephens, 1969), with little emphasis on water quality.

With regard to source/sink effects, the above quality data suggested the existence of a large net source term for both N and P. The values of these terms, however, were quite elusive and therefore several trial values were used. Likewise, the initial concentrations at the various nodes were sometimes set at zero for convenience, or assigned some assumed values. The discussions on the individual computer runs provide additional information on these trial values.

In the computation of dispersion coefficients, the constants used were those associated with sand and are likely to be higher than corresponding values for muck. The reason for this approach was lack of data for muck soils.

Groundwater Model

Description of the System—

Location of cross-section— The main cross-section considered in this study was one originating at the southwest portion of the basin and extending to its northeast boundary (see Figures 23 and 24). Two main geologic formations exist in the area: the shallow clastic aquifer and the deep and highly permeable Floridan Aquifer. The flow pattern within this cross-section depends upon the permeabilities of these formations and the flow boundary conditions. Water quality conditions are influenced by the activities occurring on the surface of the basin.

Delineation of boundaries— In the model developed by Freeze and Witherspoon (1966), the shape of vertical cross-sections considered was rectangular, with an irregular top boundary representing the water table. Also, they assumed that no flow occurred across the left, bottom and right boundaries of the system.

While many well-defined basins should conform fairly satisfactorily with these no-flow assumptions, it becomes apparent that some violations should be expected in more complex systems. Such is the case in the cross-section under study, shown in Figure 44. Since flow in the Floridan Aquifer is predominantly horizontal, the portions of the left and right boundaries located in this aquifer required attention. Reasonable estimates of flow across these two portions could be obtained from piezometric and permeability data. Thus, the original no-flow condition in each boundary portion was replaced by a flow specification.

In a qualitative discussion of shallow aquifers, Freeze and Witherspoon (1967) generalized that, barring unusual permeability configurations, the water table surface should roughly follow the topographic surface. Thus, in many cases, topographic divides (ridges or depressions) indicate corresponding hydrologic divides. In the shallow formation under consideration in Figure 44, the left boundary was located in the vicinity of a topographic ridge, and the right boundary near a depression. An alternative location for the right boundary might have been at the nearby ridge. In the absence of data indicating the contrary, a no-flow condition across both boundaries selected was assumed valid.

Finally, it is recognized that the existence of Gourd Neck Spring implies the existence of a vertical flow component in its vicinity. It was assumed that the bottom boundary was located at a sufficient distance away from the spring to insure that the vertical flow component across the boundary would, in effect, be negligible. If additional data or calculations should indicate significant vertical flows in the vicinity of this assumed boundary, its downward relocation would be necessary to conform with the no-flow condition.

Permeability estimates— To improve upon the simplified geologic picture presented above, additional data were sought from well logs. The locations of these wells, drilled by the U.S.G.S., were indicated on the master project map reproduced in Figure 25. Since none of these wells lay exactly on the vertical cross-section under study, the delineation of geologic boundaries involved extrapolation and judgement.

The boundaries between the different formations, superimposed on a grid system, are shown in Figure 45. Also indicated are the permeability values assumed for these formations. In the shallow region, these estimates are within perhaps an order of magnitude. The permeability value for the Floridan Aquifer was estimated from the results of pumping tests near Orlando (Lichtler, Anderson and Joyner, 1966). Due to the widespread existence of solution channels within the latter formation, its permeability should be viewed from a macroscopic standpoint. All the permeabilities indicated in Figure 45 were assumed equal in the horizontal and vertical directions. This assumption was dictated primarily by lack of data, since it is recognized that stratification produces anisotropy.

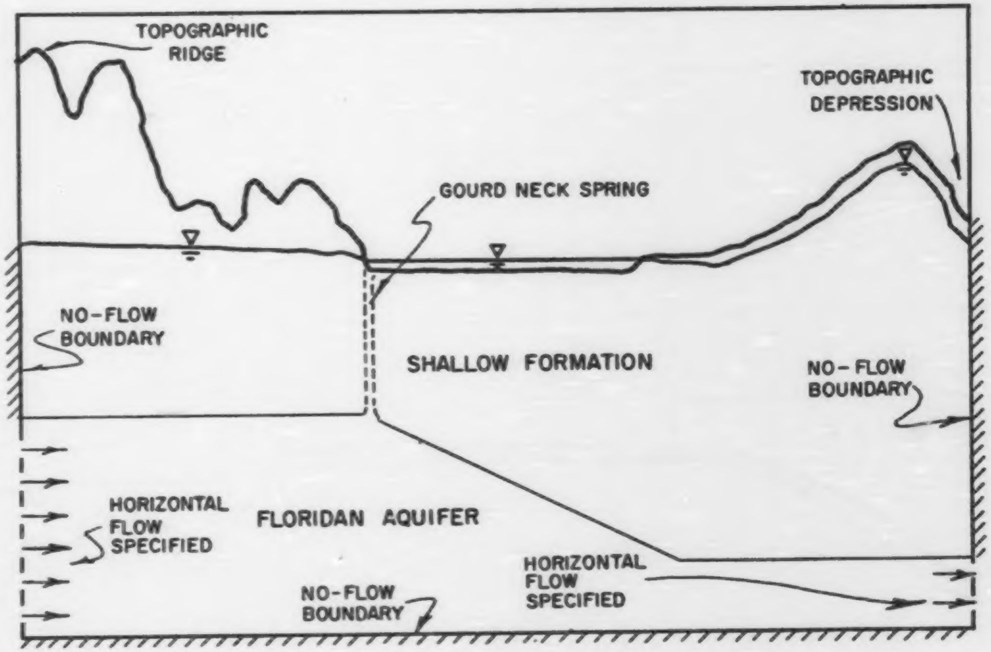

TOPOGRAPHIC RIDGE
TOPOGRAPHIC DEPRESSION
GOURD NECK SPRING
NO-FLOW BOUNDARY
SHALLOW FORMATION
NO-FLOW BOUNDARY
HORIZONTAL FLOW SPECIFIED
FLORIDAN AQUIFER
NO-FLOW BOUNDARY
HORIZONTAL FLOW SPECIFIED

Figure 44. Lateral view of cross-section AA' (figure 23), indicating flow boundary conditions.

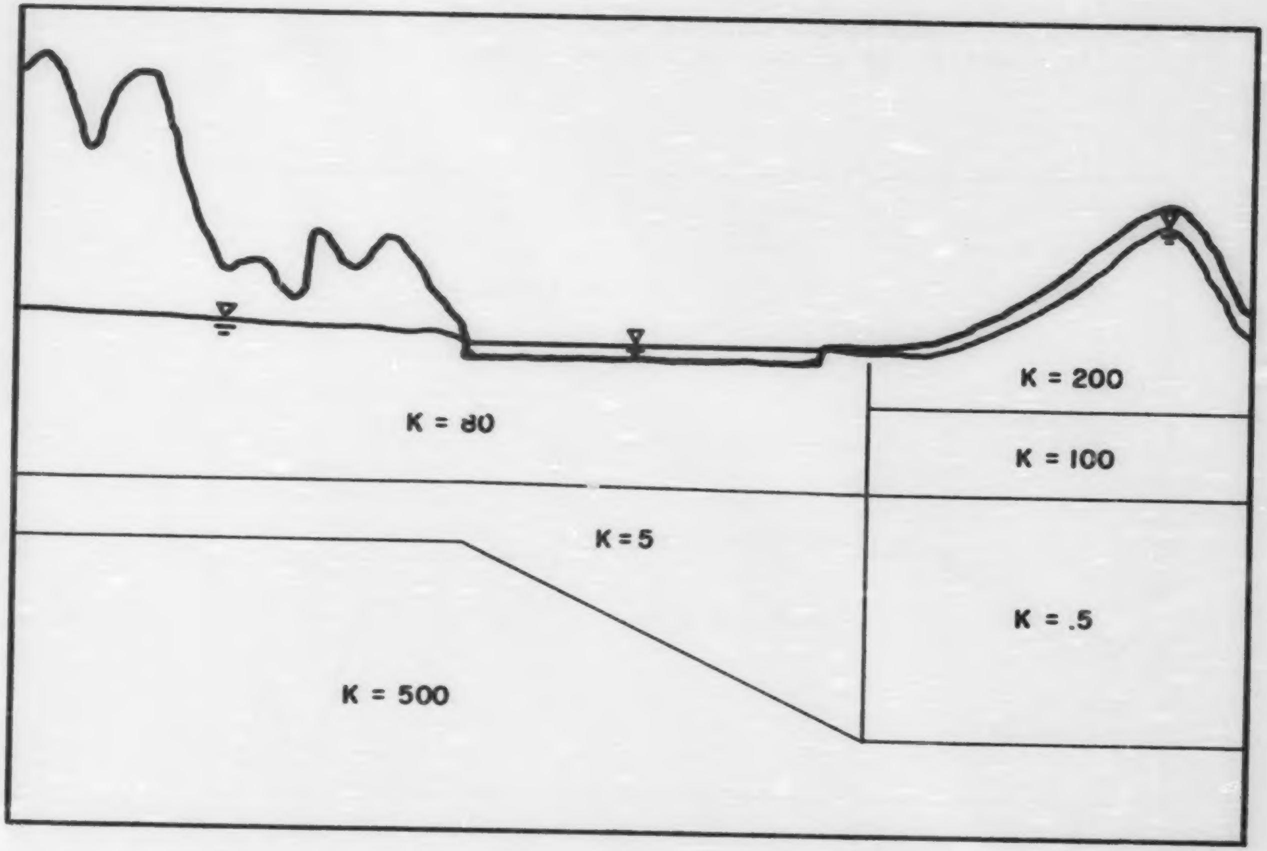

K = 80
K = 5
K = 500
K = 200
K = 100
K = .5

Figure 45. Assumed permeability (gal/day/ft^2) regions in section AA' (Figure 23). Note: 1 gal/day/ft^2 = 0.0017 m/day.

Flow Calculations—

To aid in the selection by the program of the proper form of equation (38) to be used for a given node, a node classification system was developed. Its code, illustrated in Figure 46 for the cross-section under study, is the following: 0 - interior, 1 - water table, 2 - outside the groundwater system, 3 - no-flow boundary and 4 - known head. Hydraulic heads for nodes classified as (1) and (4) are read in and kept unchanged thereafter. The heads at nodes of type (3) are allowed to change, with the no-flow condition maintained by means of an implicit image-node scheme explained elsewhere. Nodes classified as (2) are avoided in all calculations.

It is pertinent to discuss the methods used for obtaining the head values for nodes designated as (1) or (4). In the water table nodes (1), the heads at the nodes underlying Lake Apopka and the muck farms could be estimated with reasonable certainty. However, the water table location in the sandy soils on both sides of the lake could only be approximated from the limited data available from shallow observation wells.

Turning to class (4) nodes, the values specified in the row adjoining the bottom boundary were found by interpolating between the piezometric contours shown in Figure 22. The heads specified in the vicinity of the left and right boundaries of the Floridan Aquifer implicitly set the respective flow boundary conditions. Similarly, the outflow at Gourd Neck Spring was defined by specifying the head at the node located below its approximate outlet point. It is recognized that the approach used for Gourd Neck Spring is overly simplistic. However, a more realistic treatment would have required a much finer grid mesh, and consequently an increased computational cost.

Quality Calculations—

The groundwater quality formulation, developed by Shamir and Harleman (1966) and modified by Bedient (1972), utilizes the velocities computed from the flow model to predict the concentrations of substances at all nodes in the system. In this study, the quality boundary conditions consisted of concentration values specified along the top boundary. These concentrations were obtained from the quality portion of the unsaturated zone model. Nitrate was the only substance routed in the groundwater system.

Although Bedient's mathematical formulation included source/sink and decay terms, these factors could not be utilized herein due to lack of data. Thus, the only two driving forces taken into account were advection and dispersion. In the computation of the horizontal and vertical dispersion coefficients, which depend upon the respective velocities, the constants used for all the geologic formations were those proposed for sand (Hoopes and Harleman, 1965)

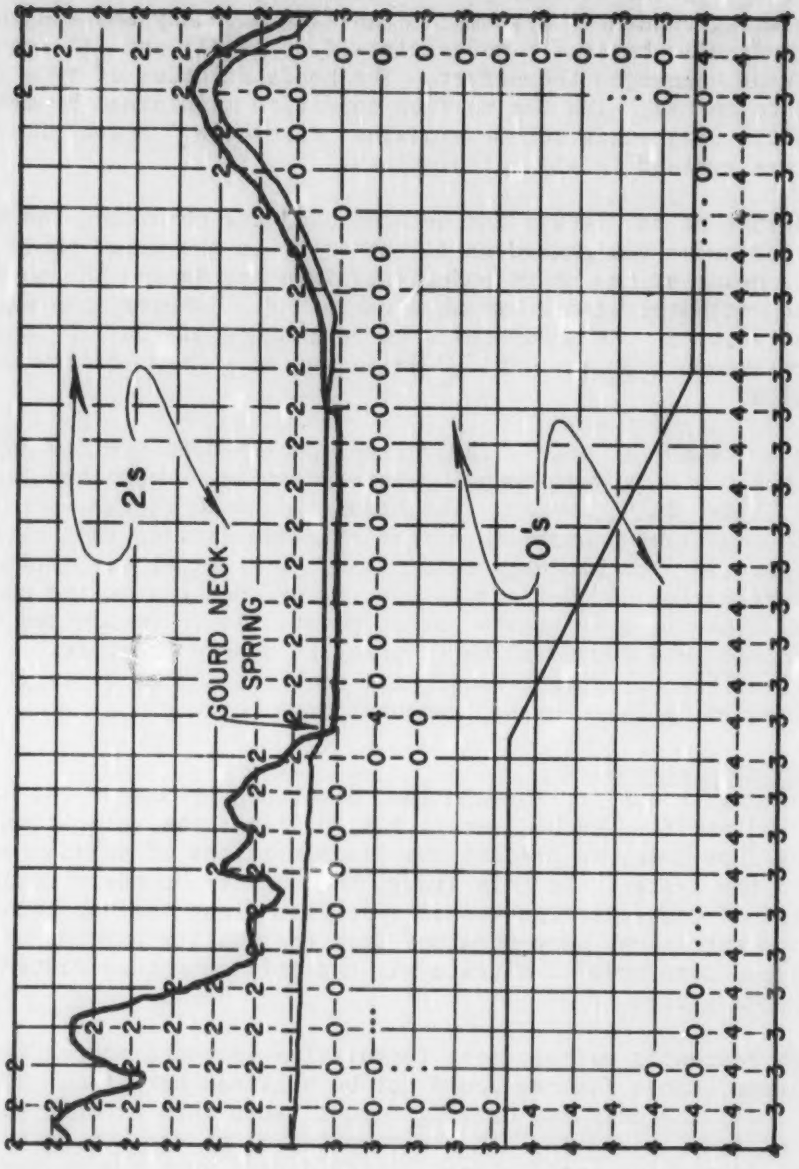

GOURD NECK
SPRING
2's
0's
2
0
3
4

Figure 46. Node classification system for groundwater flow in section AA'(Figure 23).

In a manner analogous to that in the flow model, a node classification system was developed for use in the quality calculations. Its code, which is illustrated in Figure 47, is the following: 0 - exterior, 1 - left boundary, 2 - left top, 3 - left bottom, 4 - top, 5 - bottom, 6 - right top, 7 - right bottom, 8 - right boundary, 9 - interior and 10 - known concentration. Initial concentrations must be set for all nodes not classified as (10), and the values selected depend upon the purpose and period of a particular simulation run.

INTERFACING METHODOLOGY

General Approach

The general technique used was to develop a relatively simple executive program, which in turn calls the different models in a sequential fashion. The order used for the various types of models was: (1) unsaturated zone, (2) overland flow (runcff), (3) receiving model and (4) groundwater.

The executive program utilized an overlay procedure to minimize the active data storage requirements. As part of the overlay technique, data sets were used to store the information utilized by the various models above. Permanent data sets were specified, mainly for data that were known prior to a computation run, such as catchment layouts and canal geometry. On the other hand, temporary, or scratch, sets were defined primarily for input/output operations between models.

Partitioning of the Study Area

To promote the homogeneity of model parameters, the Lake Apopka basin was partitioned into subsystems within the various model categories. A review of the previous sections indicates the following breakdown:

1. Unsaturated Zone
    a. Sandy soils located around the southern half of the lake
    b. Muck farms lying north of the lake
    c. Sandy soils north of the muck farms
2. Overland Flow (Runoff)
    a. Sandy soils described in (1a)
    b. Zellwood district in muck farms
    c. Duda district in muck farms
    d. Sandy soils indicated in (1c)
3. Surface Bodies of Water (Receiving Model)
    a. Drainage canals in Zellwood district
    b. Drainage canals in Duda district
    c. Lake Apopka
4. Groundwater
    a. S. W. to N. E. cross-section

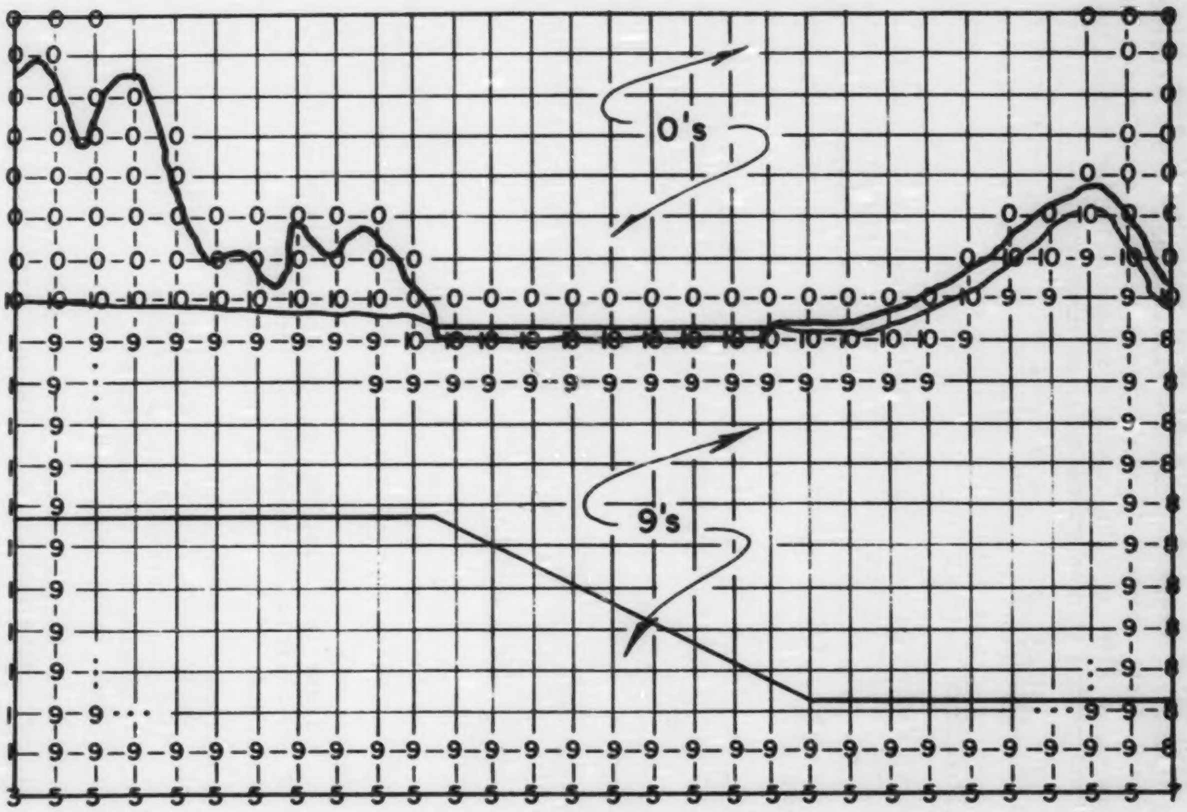


Figure 47. Water quality node classification system in section AA' (Figure 23).

An individual computer model was utilized for each of the subsystems listed above. In the executive program, these models appeared in an order dictated by their category, such as unsaturated zone or groundwater. The sequencing of models within a given category was determined arbitrarily.

Flow Chart of Models and Data Sets

A graphical illustration of the various subsystem models run and their order in the executive program is provided in Figure 48. The permanent data sets are represented by the boxes on the left hand side of this figure. One permanent set is used for each model. The temporary data sets, and some of the variables stored therein, are depicted in the right hand portion. The arrows denote the flow of information between these data sets and the models, thus representing READ and WRITE statements. Not shown in this figure are the data sets used for interfacing the flow and quality portions of both the Stormwater Management Model runoff and receiving models, since additional information on these programming aspects can be obtained elsewhere (Environmental Protection Agency, 1971). A list of variables associated with each temporary data set is given in Appendix D.

OBJECTIVES OF COMPUTER RUNS

In this investigation, the main purposes of the various simulation runs were to gain an intuitive understanding of system behavior and to ascertain the relative importance of different model parameters upon this overall behavior. Since many of the values of these parameters are not available, the model at the present stage could be viewed as an instrument for structuring data gathering efforts.

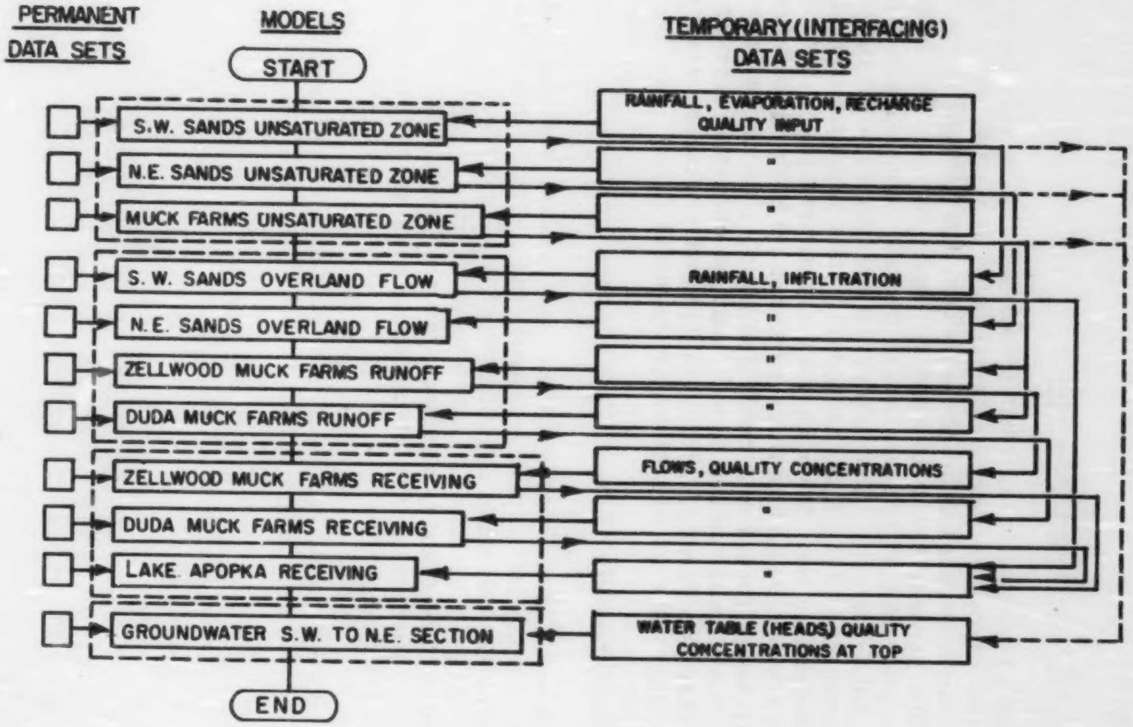

PERMANENT DATA SETS
MODELS
TEMPORARY (INTERFACING) DATA SETS
START
S.W. SANDS UNSATURATED ZONE
N.E. SANDS UNSATURATED ZONE
MUCK FARMS UNSATURATED ZONE
S.W. SANDS OVERLAND FLOW
N.E. SANDS OVERLAND FLOW
ZELLWOOD MUCK FARMS RUNOFF
DUDA MUCK FARMS RUNOFF
ZELLWOOD MUCK FARMS RECEIVING
DUDA MUCK FARMS RECEIVING
LAKE APOPKA RECEIVING
GROUNDWATER S.W. TO N.E. SECTION
END
RAINFALL, EVAPORATION, RECHARGE QUALITY INPUT
"
"
RAINFALL, INFILTRATION
"
"
"
FLOWS, QUALITY CONCENTRATIONS
"
"
WATER TABLE (HEADS) QUALITY CONCENTRATIONS AT TOP

Figure 48. Computational flow chart of program package, showing the use of data sets.

SECTION IX

RESULTS AND CONCLUSIONS

INTRODUCTION

This section discusses the results of the various simulation runs conducted in this study and the conclusions derived from them. The main items considered are sample results for the individual models, interpretation of these results for different subsystems within the study area and evaluation of the impact of different model parameters. These trial runs indicated the need for additional data for proper calibration, especially for the quality models. Thus, comprehensive interfacing runs were felt to be unwarranted. Instead, a limited amount of interfacing was conducted for the purpose of checking programming instructions. Conclusions and suggestions for further research are presented from the standpoint of both general modeling efforts and the Lake Apopka basin.

SAMPLE RESULTS OF INDIVIDUAL MODELS

Representative computational results are discussed for each of the three model types: (1) surface water, (2) unsaturated zone, and (3) groundwater zone. Category (1) includes overland flow (runoff) and flow in surface bodies of water.

Surface Water

Overland Flow—

Two separate overland flow models were utilized, depending on the degree of channelization in a given area: (1) the kinematic wave method (Eagleson, 1970) and (2) the runoff portion of the Stormwater Management Model (Environmental Protection Agency, 1971).

Kinematic wave model— This model was applied to the sandy soils in the Lake Apopka basin. Its results are illustrated for a catchment located north of the muck farms area. The catchment geometry parameters and the assumed boundary conditions are indicated in Figure 49. Also shown are the ponding depths obtained from the unsaturated zone

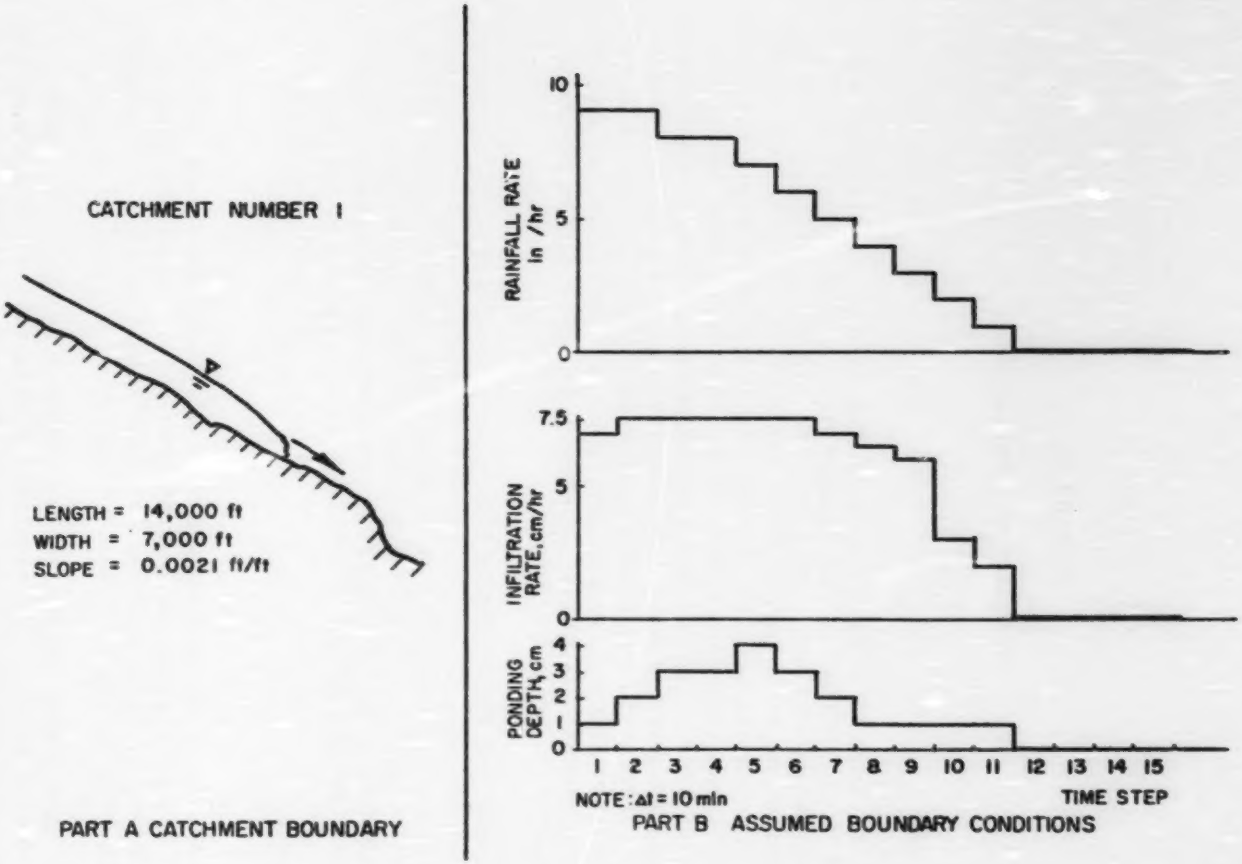


Figure 49. Catchment geometry and boundary conditions used in kinematic wave overland flow model demonstration run.

model and used as inputs to this formulation. The necessary averaging calculations involving these boundary conditions are explained more fully in Appendix A.

The predicted outflow hydrograph resulting from the conditions depicted in Figure 49 is shown in Figure 50. Its shape and characteristics conform to those proposed by Eagleson for these relative values of storm duration and time of concentration. It may be observed that the rainfall intensity used is very high. Due to the high infiltrative capacity of these sandy soils, ordinary rainstorms would produce little or no overland flow. This conclusion has been confirmed by agricultural personnel in the area.

Also plotted in Figure 50 is a graph of the predicted phosphorous flux versus time at the catchment outlet. As was the case with the outflow hydrograph, only severe rainstorms should produce appreciable sediment loads in the sandy areas. The calculation of phosphorous content in sediments, discussed in Appendix E, was based on several simplifying assumptions. A comparison of predicted loads in other catchments under similar hydrologic conditions pointed out the significance of the slope on sediment transport. That is, erosion from catchments having gentle slopes should occur only under extremely high rainfall conditions.

Stormwater runoff model— This formulation was utilized for the artifically drained muck farms on the north shore of Lake Apopka. Figure 51 constitutes a map of a catchment in the Duda district. The hydrologic boundary conditions for this catchment are also indicated therein. The numerical technique used in this model permitted the utilization of the original boundary condition values, without the intermediate averaging procedure required in the analytical kinematic wave method.

All the overland flow from the catchment is assumed to constitute a point source at an inlet point. The computed flow hydrograph at this point is plotted in Figure 52. For ordinary rainstorms, overland flow is of relatively little significance in the muck farms.

The model computations yielded a suspended solids flux of zero for all time intervals. Thus, the phosphorous contribution was also zero. The same result was obtained throughout the muck farms and it appears reasonable in view of the essentially flat ground surface in the area.

Receiving Water—
The receiving model was applied to the drainage canals in the muck farms and subsequently to Lake Apopka. The results for these two areas are discussed separately.

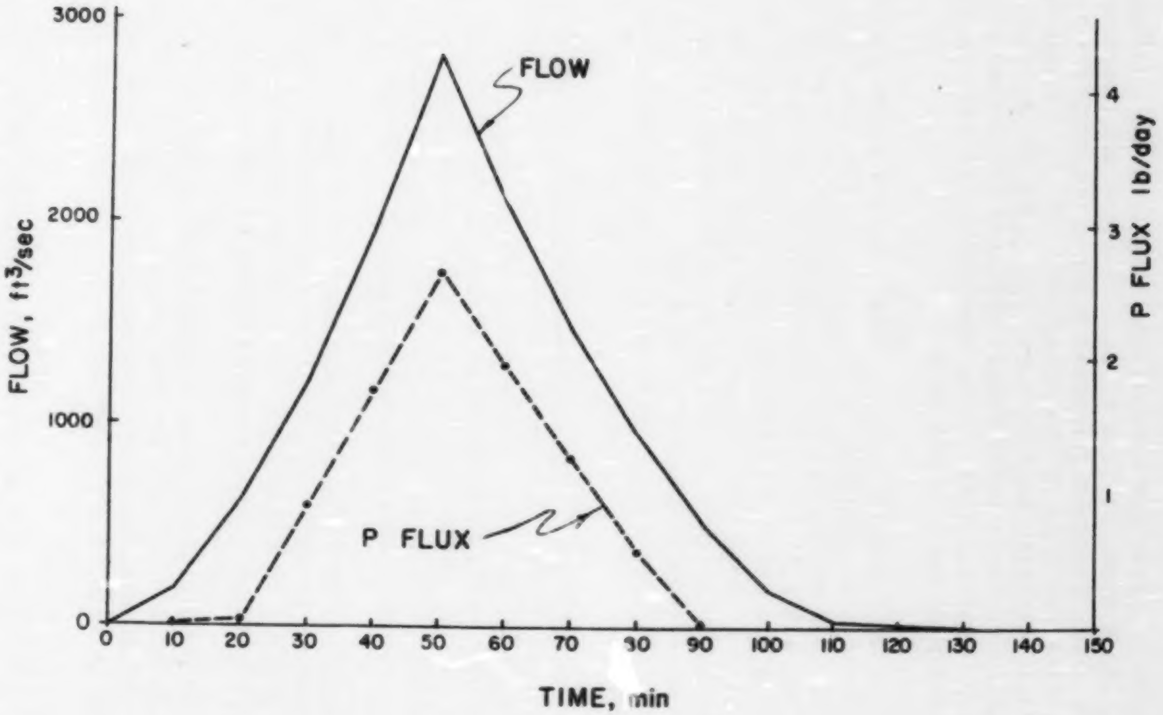
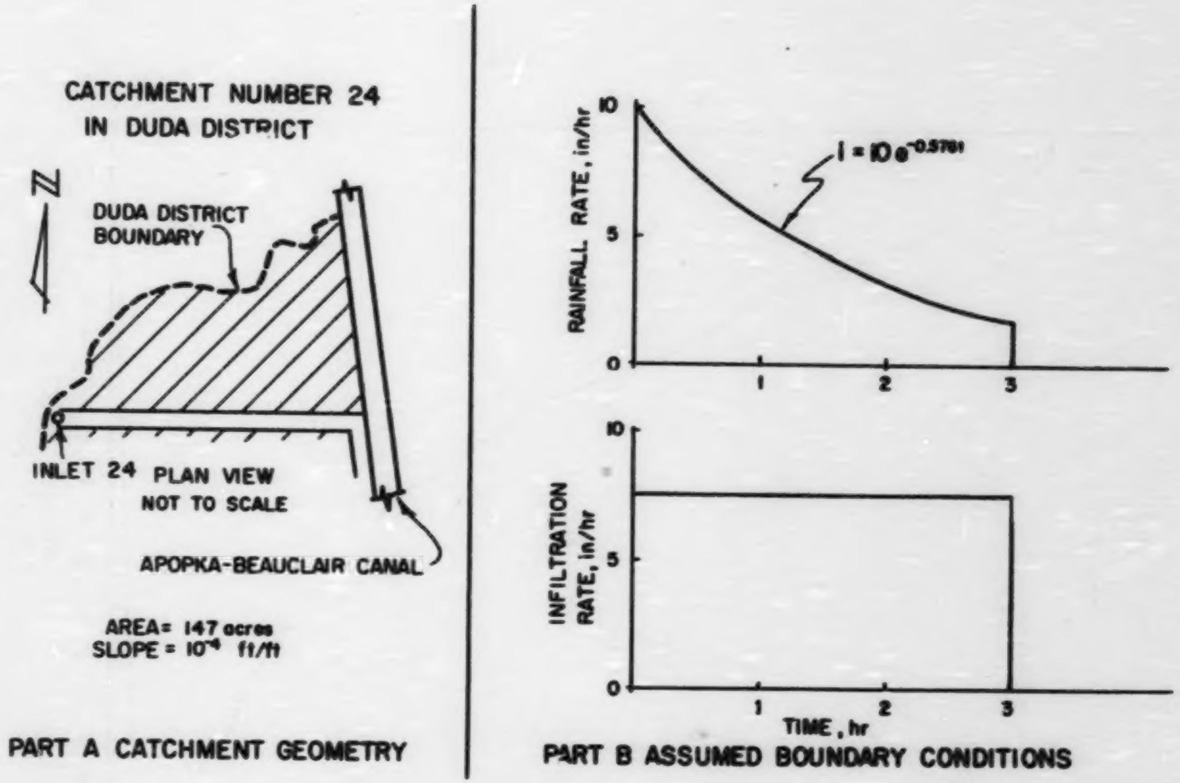


Figure 50. Predicted outflow hydrograph from catchment number 1 in sandy soils area.


CATCHMENT NUMBER 24
IN DUDA DISTRICT
N
DUDA DISTRICT
BOUNDARY
INLET 24
PLAN VIEW
NOT TO SCALE
APOPKA-BEAUCLAIR CANAL
AREA= 147 acres
SLOPE = 10^{-4} ft/ft
RAINFALL RATE, in/hr
10
5
0
1
2
3
I = 10 e$^{-0.578t}$
INFILTRATION
RATE, in/hr
TIME, hr

PART A CATCHMENT GEOMETRY

PART B ASSUMED BOUNDARY CONDITIONS

Figure 51. Catchment geometry and boundary conditions used in demonstration run of runoff portion of Stormwater Management Model.

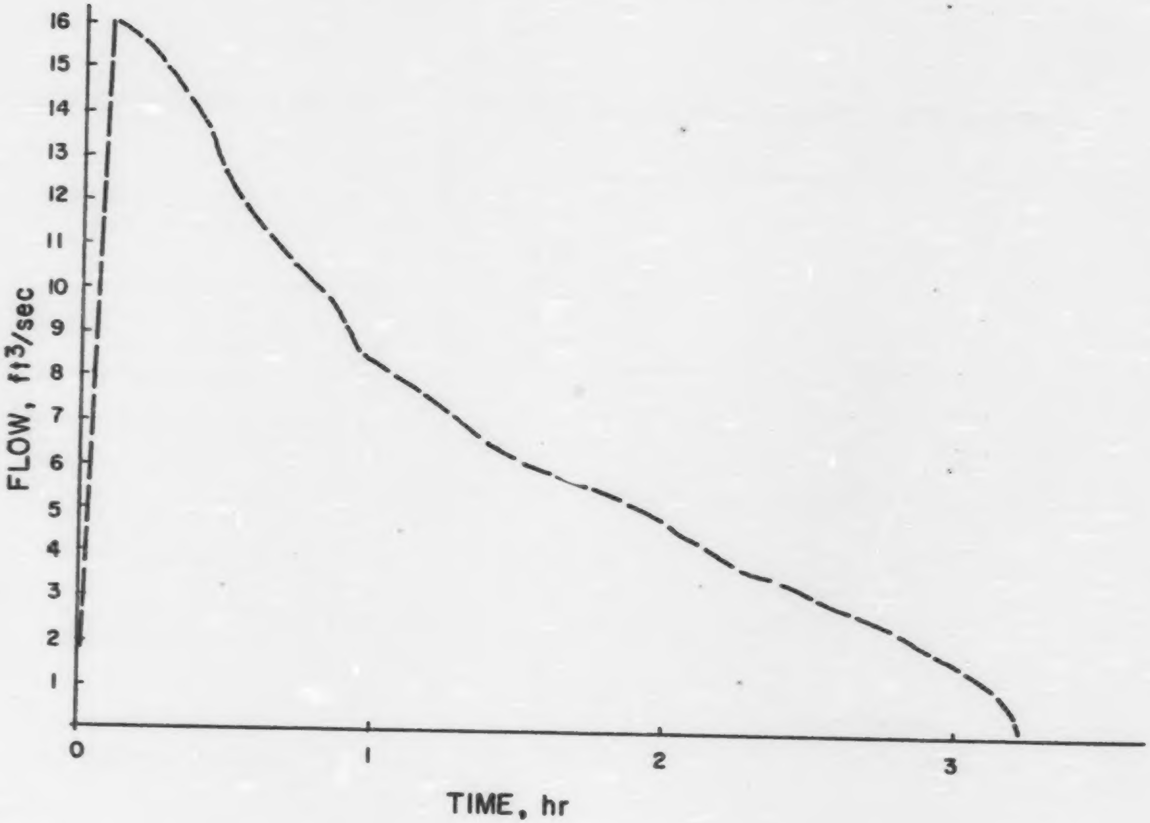


Figure 52. Predicted outflow hydrograph for catchment 24 in the Duda District.

Muck farms canals— The location of two adjoining junctions (numbers 56 and 57) in the Zellwood area is shown in Figure 53 and also in Figure 34. The period under study was that during the simulated rainstorm given in Figure 49. Indicated in Figure 53 are the pumpage rates used in the simulation. These assumed rates were quite high because they were based upon maximum pumping capacities.

Figure 54 contains a plot of the calculated stage at the upstream junction for several time steps. The corresponding heads at the downstream junction are slightly lower. As can be observed, the stage decreased sharply after the rainfall ceased. Several flow values between the two points are plotted in Figure 55.

Turning to the water quality results, Figure 56 contains a plot of nitrogen and phosphorous concentrations versus time, at the upstream junction (57). Nutrient inputs originated primarily from the mole drains. Source/sink reactions between water and soil were not considered.

Calibration of the relationships shown in Figures 54, 55 and 56 was precluded by the lack of short-term data.

Lake Apopka— Figure 39 constitutes a map of Lake Apopka with the approximate location of the junctions defined for the lake receiving model. Average inputs used for the simulation are also shown. The hypothetical rainfall conditions and pumpage rates used were the same as those utilized for the muck farms simulation. Overland flow contributions from the sandy soils catchments were neglected.

The predicted stages for junction 3 (see Figure 39) are plotted in Figure 57. In the first few hours the stage increased rapidly, due primarily to rainfall. Thereafter it rose more slowly, in response only to the pumpage inflows. Most of the corresponding stages at other junctions were within 0.01 ft of the values obtained for junction 3. This indicated the lack of appreciable hydraulic gradients across the lake. The predicted flows between junctions 3 and 8 are provided in Figure 58.

To investigate the movement of nutrients, their initial concentrations at the various junctions were set at zero. Also, source/sink and decay effects were neglected, thus treating these substances as conservative. Predicted increases in concentrations resulting from the imposed boundary loads were rather small. System response can be illustrated by an examination of the results obtained for junction 3, located in the vicinity of the pumping centers. Concentrations are plotted in Figure 59. Predicted concentrations for junctions farther away from the pumps were much lower. The generally low values obtained point out the need to consider water quality changes over longer time horizons.

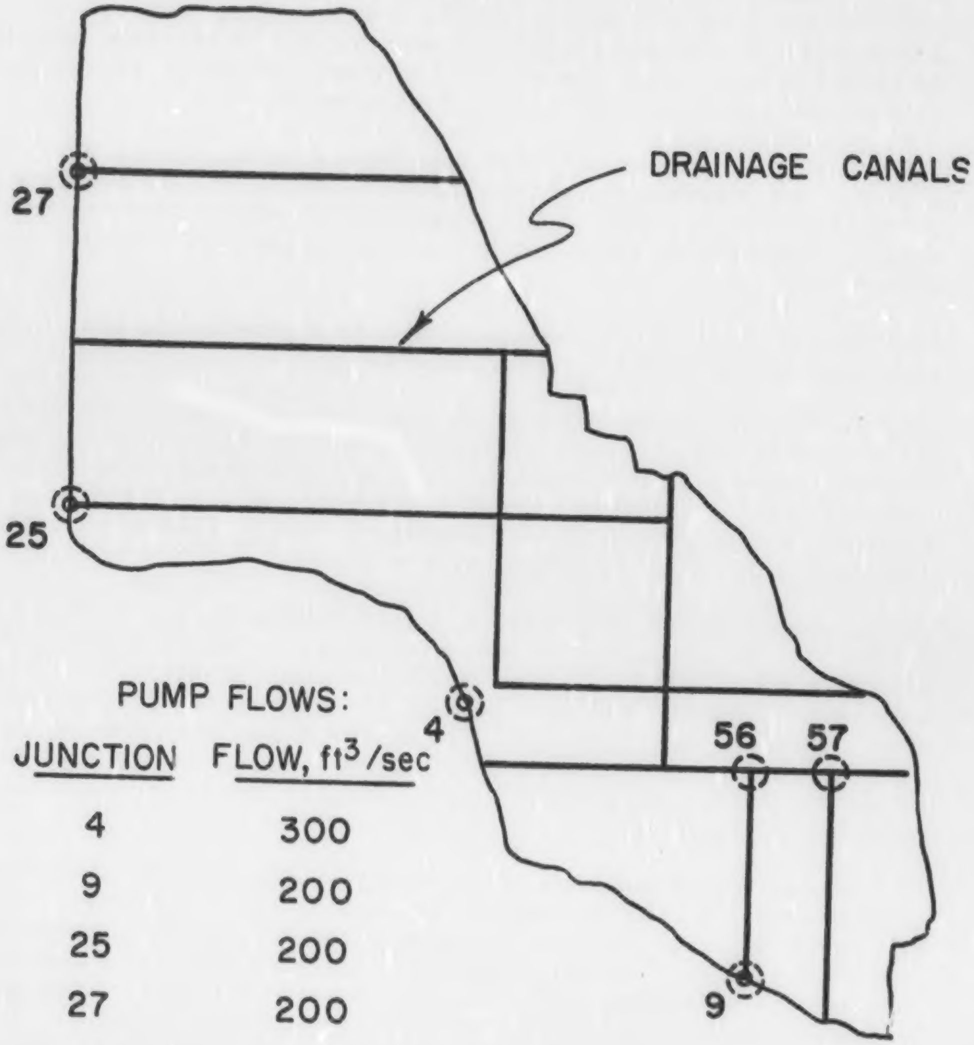

DRAINAGE CANALS
27
25
4
56
57
9
PUMP FLOWS:
JUNCTION
FLOW, ft³/sec
4
300
9
200
25
200
27
200

Figure 53. Map of Zellwood drainage district showing location of various junctions.

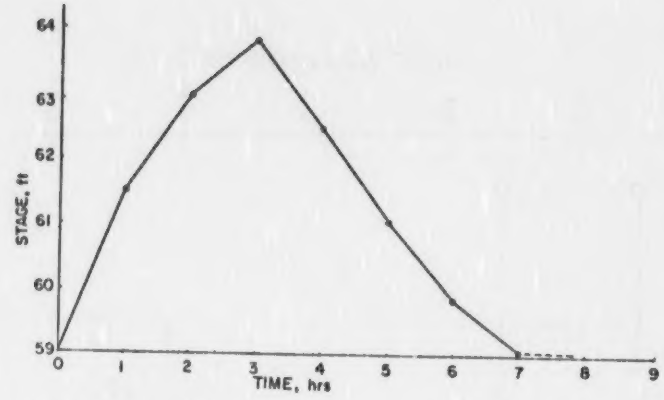


Figure 54. Predicted stages at junction 57 in Zellwood district.

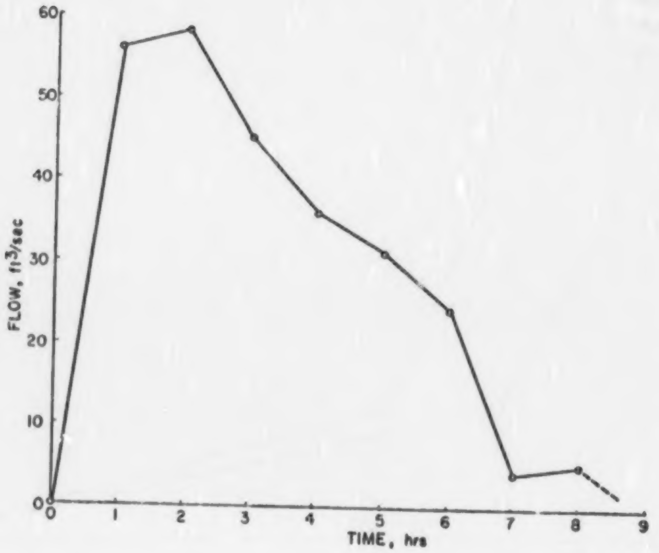


Figure 55. Predicted flows between junctions 56 and 57 in Zellwood district.

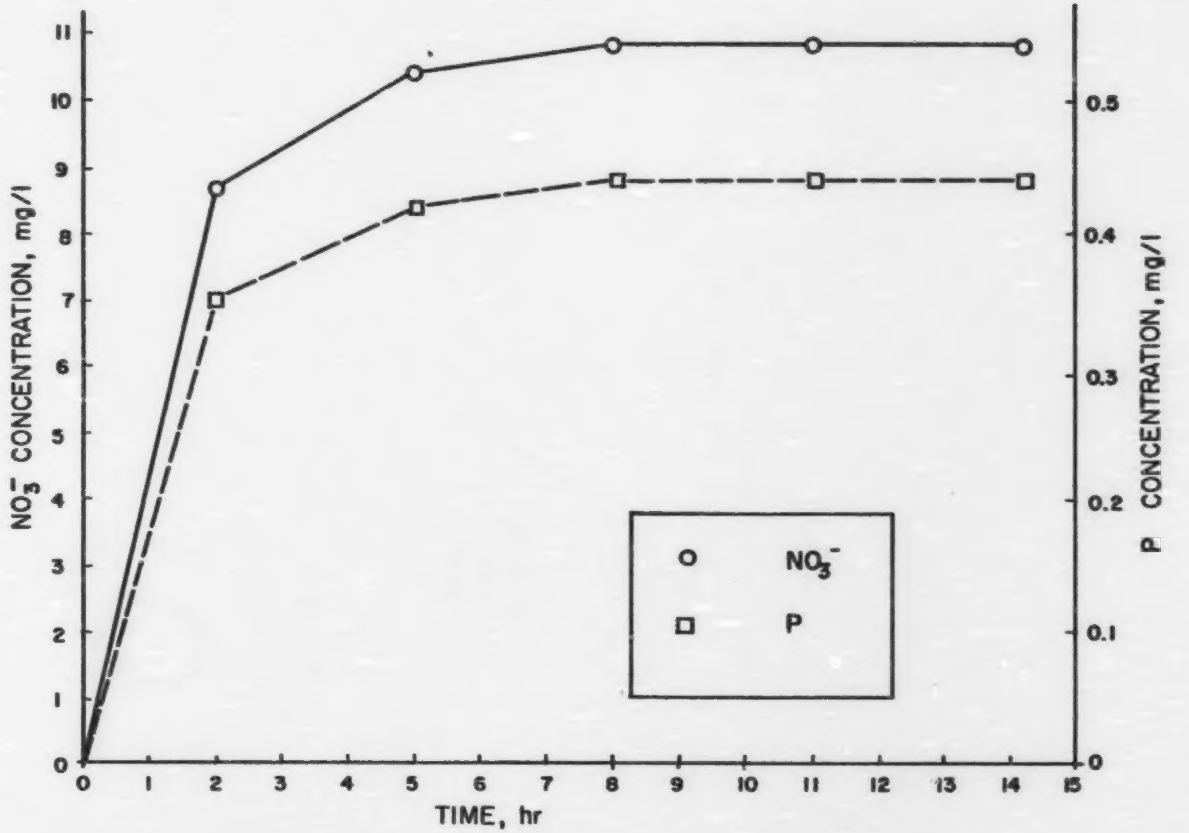


Figure 56. Predicted nitrate and phosphorous concentrations at junction 57 in Zellwood district.

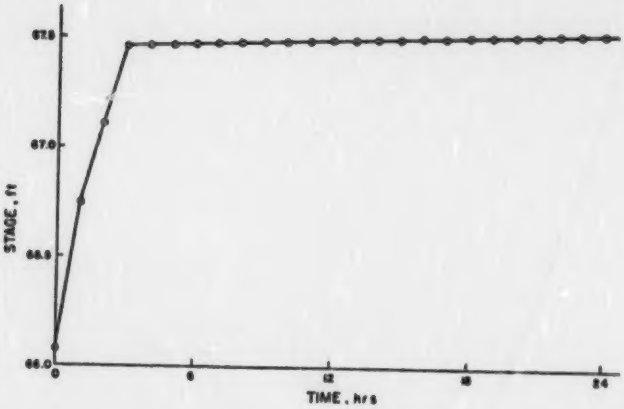


Figure 57. Predicted stages at junction 3 in Lake Apopka

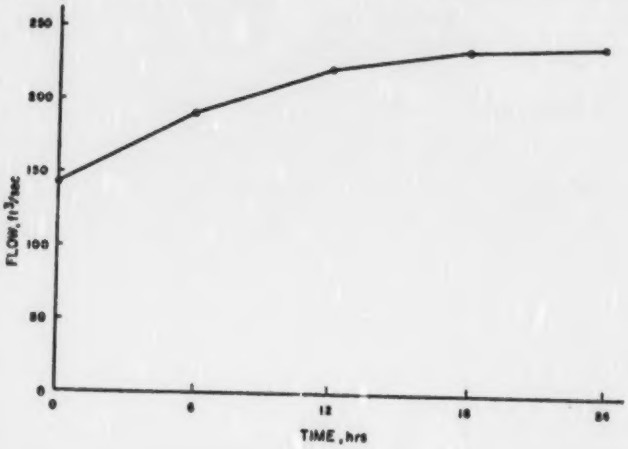


Figure 58. Predicted flows from junction 3 to junction 8 in Lake Apopka.

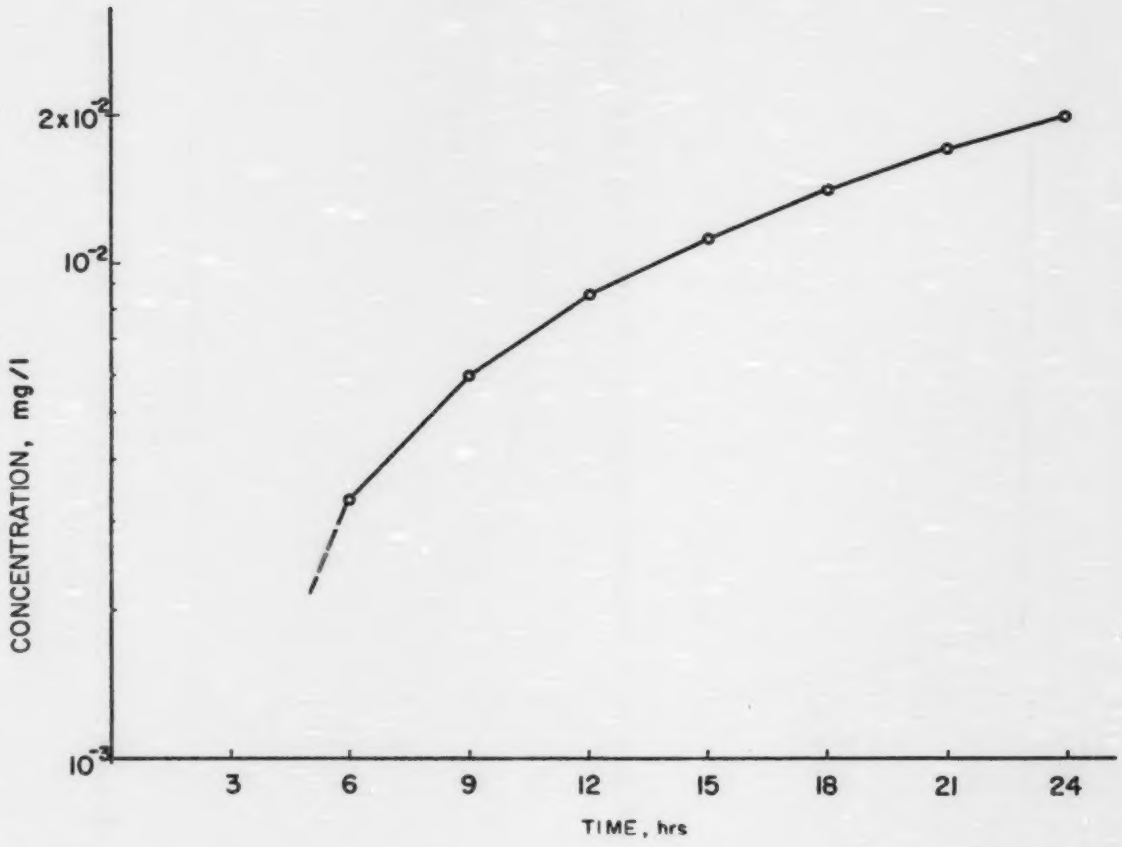


Figure 59. Predicted nitrate concentrations at junction 3 in Lake Apopka.

Unsaturated Zone

The unsaturated zone model was applied to the muck farms areas and two areas in the sandy soils. Results for the sandy region north of the muck farms are presented herein.

Figure 60 consists of a graphical representation of the boundary condition flow values used in a particular run. The three boundary conditions are: rainfall, evaporation, and recharge. Computed soil moisture profiles at different times are plotted in Figure 61. In the initial profile, the moisture content decreased with elevation. Subsequently, as a consequence of high rainfall, the moisture at the upper nodes increased significantly. The uppermost node became saturated and a temporary ponding condition resulted. Gradually the entire profile approached saturation. Withdrawal of water by plants was found to have little appreciable effect in this short simulation run. However, it should be important on a long term basis. In the muck farms, the predicted withdrawal flows at the mole drains were significant, with a corresponding impact on soil moisture conditions. In practice, the efficiency of the mole drains might be much lower.

The water quality results corresponding to the sandy soil profile shown in Figure 60 are presented in Figure 62. Indicated therein are the upper boundary condition, which was set at the initial time step, and the predicted concentration profiles at successive time steps. Source/sink reactions between the percolating water and the soil and nutrient withdrawals by plants were not considered in this run. Insufficient time was provided in this run for significant downward movement of nitrate, with buildup expected to have occurred between the top two nodes. Thus, these results illustrate primarily the phenomenon of dispersion.

Data were not available to verify or calibrate the quality model in the sandy soils. In the muck farms, previous data collected during both wet and dry periods indicated fairly uniform concentration profiles with depth. Also, the measured concentrations were rather high. These data suggested the importance of nutrient release from the muck soil, and therefore, the need to gain further insight into source/sink rates.

Groundwater

The groundwater model results presented herein are those for vertical cross-section AA', which extends from the southwest portion of the Lake Apopka basin toward the northeast (see Figure 22). The location of this section was illustrated previously. Also discussed earlier were its estimated boundary conditions and permeability configuration.

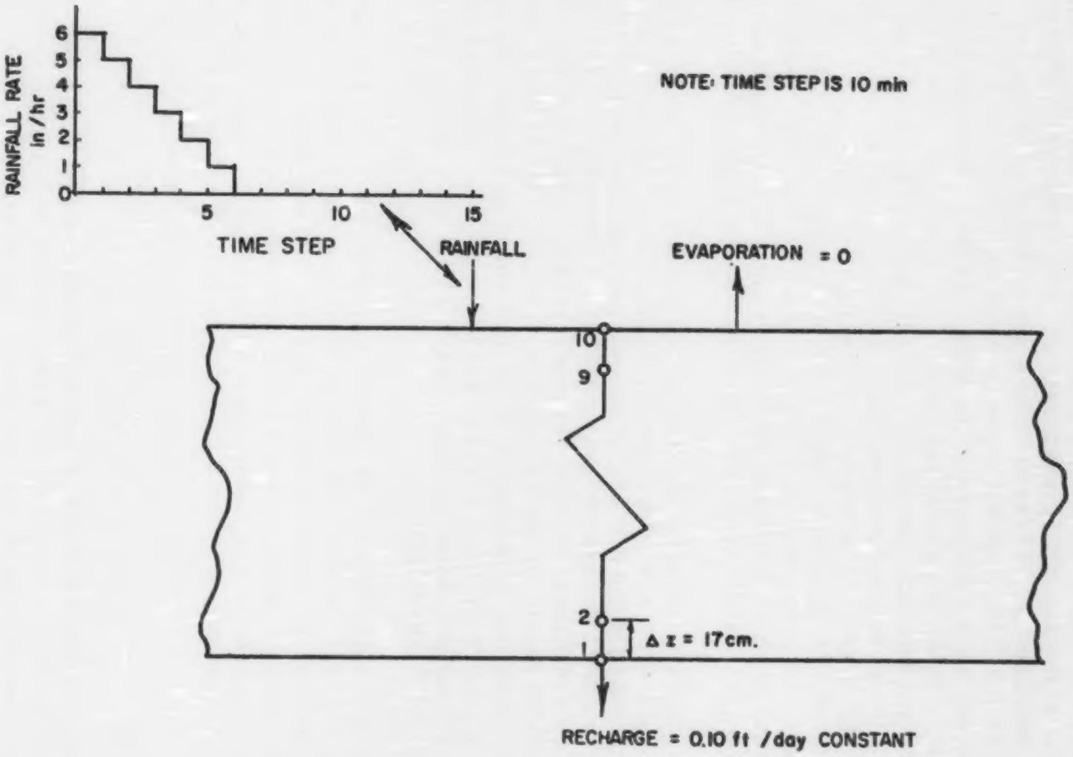

RAINFALL RATE in/hr
0
1
2
3
4
5
6
5
10
15
TIME STEP
RAINFALL
NOTE: TIME STEP IS 10 min
EVAPORATION = 0
10
9
2
1
Δ z = 17cm.
RECHARGE = 0.10 ft /day CONSTANT

Figure 60. Boundary conditions used in a run of the unsaturated zone model for the sandy soils.

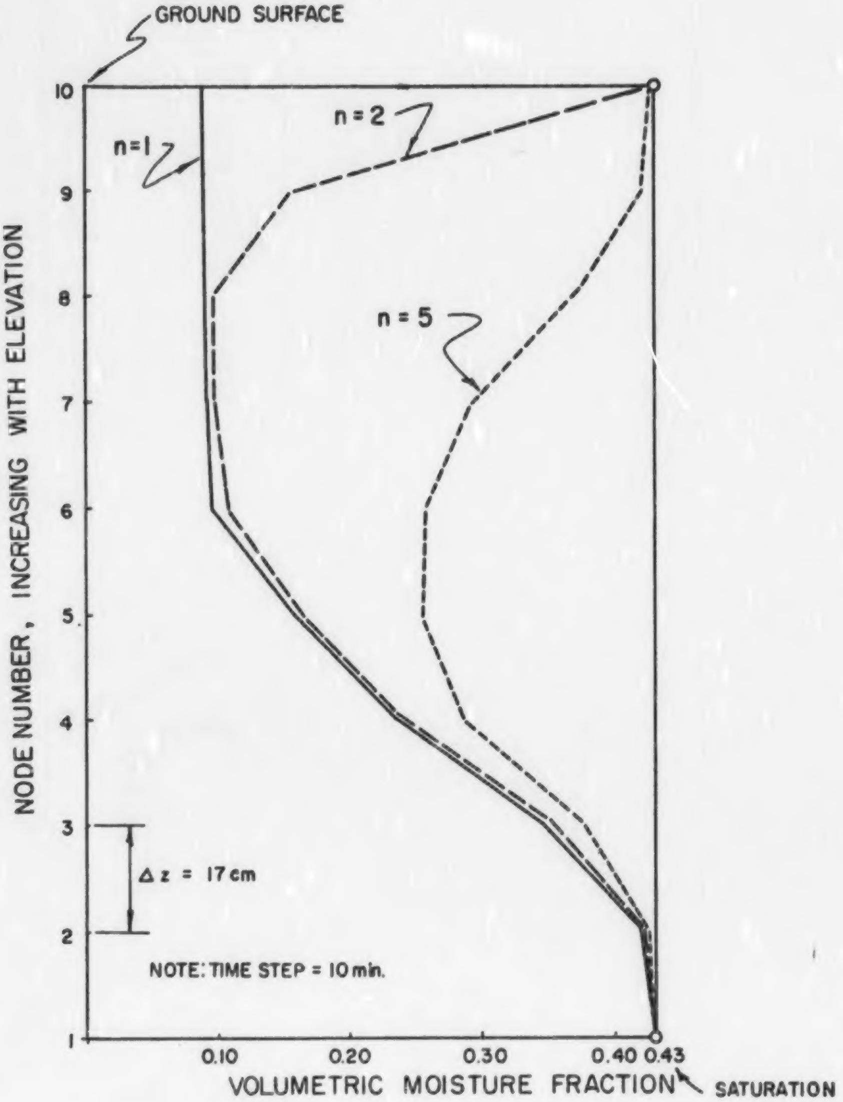


Figure 61. Predicted moisture profiles in the sandy soils at different time steps.

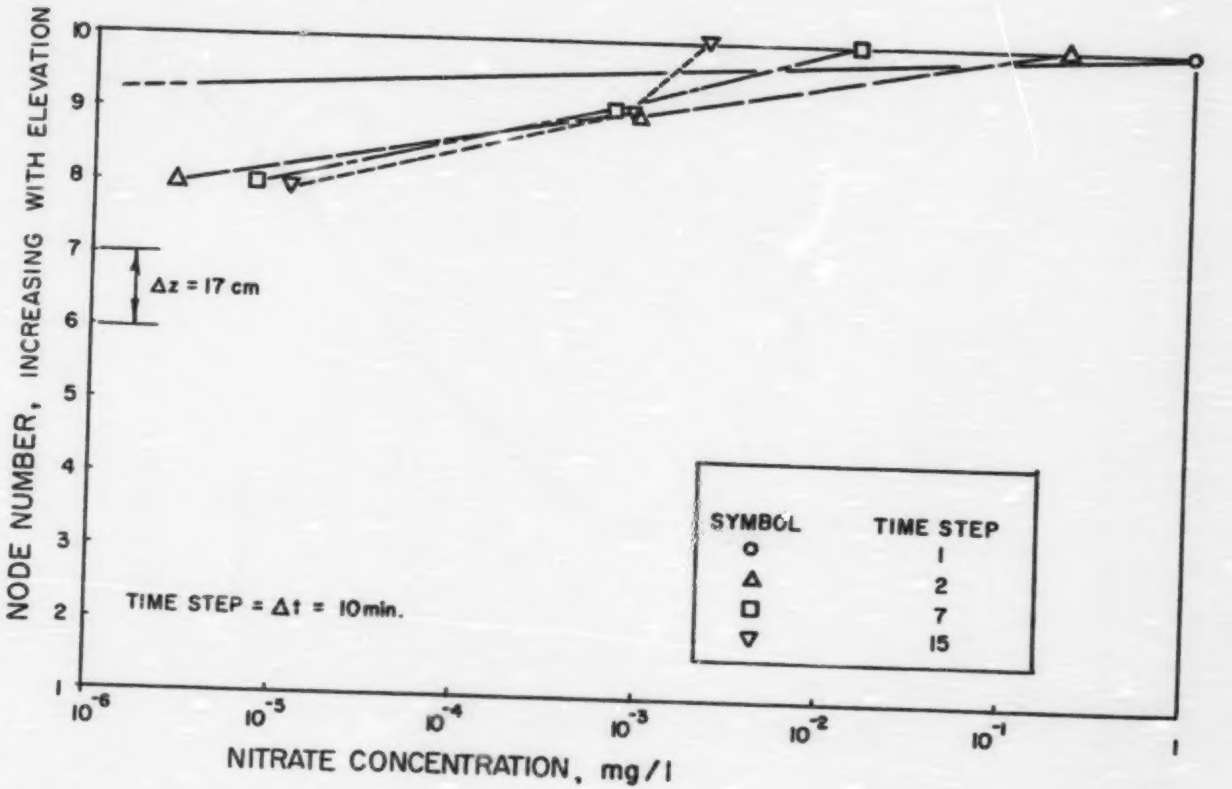


Figure 62. Predicted nitrate concentration profiles in the sandy soils at different time steps.

Figure 63 is a reproduction of a computer tabulation of predicted hydraulic heads for all nodes within the cross-section. These were the values obtained after 100 iterations of the steady-state flow model. The values for water table nodes and other nodes of known head (classes 1 and 4, respectively) were provided initially and remained unchanged throughout.

To graphically analyze the flow patterns in this section, it would be possible to draw flow nets, that is, orthogonal families of equipotential and stream lines. However, prior to utilizing this approach it would be desirable to improve the predictive accuracy of the model by obtaining additional data on boundary conditions and permeabilities. Specifically, data for the sandy soils area north of the muck farms and its underlying formations are scarce. Several preliminary runs for this cross-section indicated that the overall flow patterns are more sensitive to changes in the permeability configuration than to fluctuations in flow boundary conditions.

The water quality portion of the groundwater model was tested by specifying nitrate concentrations of unity at various nodes along the water table boundary of the cross-section. The ensuing concentrations within the section were predicted and tabulated at different times. Figures 64, 65 and 66 constitute contour maps obtained from computer printouts of these values. The respective times within the simulation period are indicated.

To investigate the gradual increase in concentrations at the various nodes as a result of the boundary conditions, the initial values of these concentrations were arbitrarily set equal to a small positive number. This number (10^{-31}) was used rather than zero to avoid the prediction of very small negative concentrations resulting from numerical oscillations. An examination of Figures 64, 65 and 66 reveals that the movement of nitrate in groundwater is predominantly downward, with little contribution to Lake Apopka. The area of Gourd Neck Spring merits further investigation since short-circuiting effects might be significant.

Numerical instabilities are likely to result in this model in situations where the time step exceeds the time of water travel between any two nodes. However, the problem can be avoided effectively by reducing the time step. Additional insight and comments about this matter are provided by Bedient (1972).

DISCUSSION OF INVESTIGATIVE RUNS

The main features considered in these simulation runs were trial variations in model parameters. These changes were dictated by the individual model results.

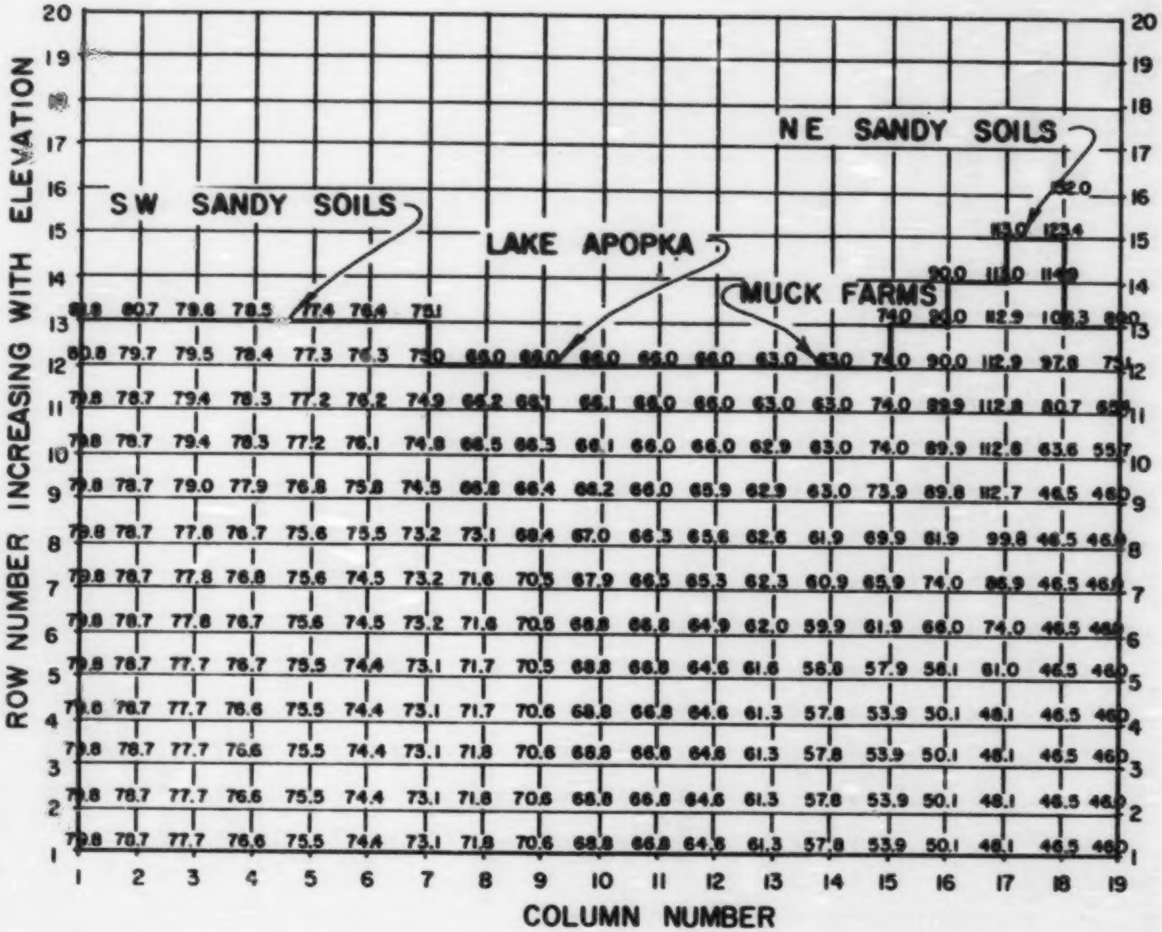

ROW NUMBER INCREASING WITH ELEVATION
COLUMN NUMBER
SW SANDY SOILS
LAKE APOPKA
MUCK FARMS
NE SANDY SOILS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
132.0
113.0 123.4
90.0 113.0 114.9
81.8 80.7 79.6 78.5 77.4 76.4 75.1 74.0 90.0 112.9 108.3 89.0
80.8 79.7 79.5 78.4 77.3 76.3 75.0 66.0 66.0 66.0 66.0 66.0 63.0 63.0 74.0 90.0 112.9 97.8 75.1
79.8 78.7 79.4 78.3 77.2 76.2 74.9 66.2 66.1 66.1 66.0 66.0 63.0 63.0 74.0 89.9 112.8 80.7 65.8
79.8 78.7 79.4 78.3 77.2 76.1 74.8 66.5 66.3 66.1 66.0 66.0 62.9 63.0 74.0 89.9 112.8 63.6 55.7
79.8 78.7 79.0 77.9 76.8 75.8 74.5 66.8 66.4 66.2 66.0 65.9 62.9 63.0 73.9 89.8 112.7 46.5 46.0
79.8 78.7 77.8 76.7 75.6 75.5 73.2 73.1 68.4 67.0 66.3 65.6 62.6 61.9 69.9 81.9 99.8 46.5 46.0
79.8 78.7 77.8 76.8 75.6 74.5 73.2 71.6 70.5 67.9 66.5 65.3 62.3 60.9 65.9 74.0 86.9 46.5 46.0
79.8 78.7 77.8 76.7 75.6 74.5 73.2 71.6 70.5 68.8 66.6 64.9 62.0 59.9 61.9 66.0 74.0 46.5 46.0
79.8 78.7 77.7 76.7 75.5 74.4 73.1 71.7 70.5 68.8 66.8 64.6 61.6 56.8 57.9 56.1 61.0 46.5 46.0
79.8 78.7 77.7 76.6 75.5 74.4 73.1 71.7 70.6 68.8 66.8 64.6 61.3 57.8 53.9 50.1 48.1 46.5 46.0
79.8 78.7 77.7 76.6 75.5 74.4 73.1 71.8 70.6 68.8 66.8 64.6 61.3 57.8 53.9 50.1 48.1 46.5 46.0
79.8 78.7 77.7 76.6 75.5 74.4 73.1 71.8 70.6 68.8 66.8 64.6 61.3 57.8 53.9 50.1 48.1 46.5 46.0
79.8 78.7 77.7 76.6 75.5 74.4 73.1 71.8 70.6 68.8 66.8 64.6 61.3 57.8 53.9 50.1 48.1 46.5 46.0

Figure 63. Predicted heads in cross-section AA' (Figure 23) after 100 iterations.

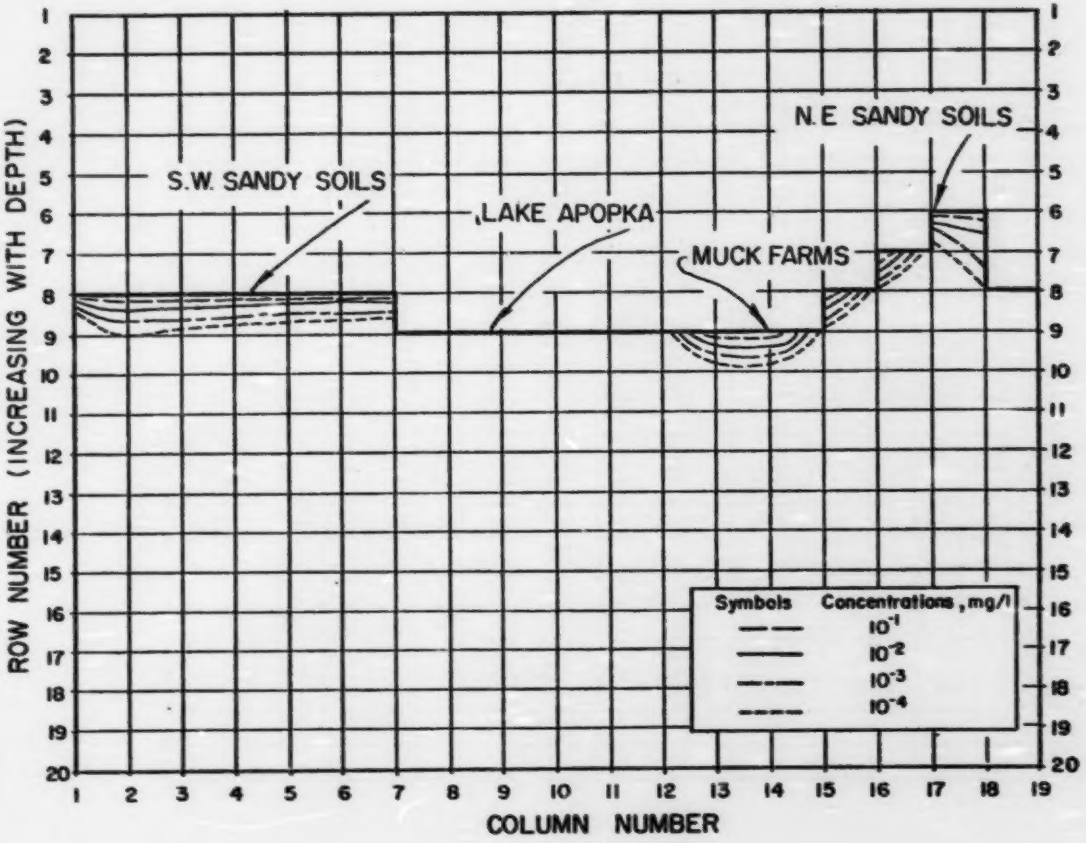


Figure 64. Predicted nitrate concentration contours in cross-section AA' (Figure 23) after one hour of input.

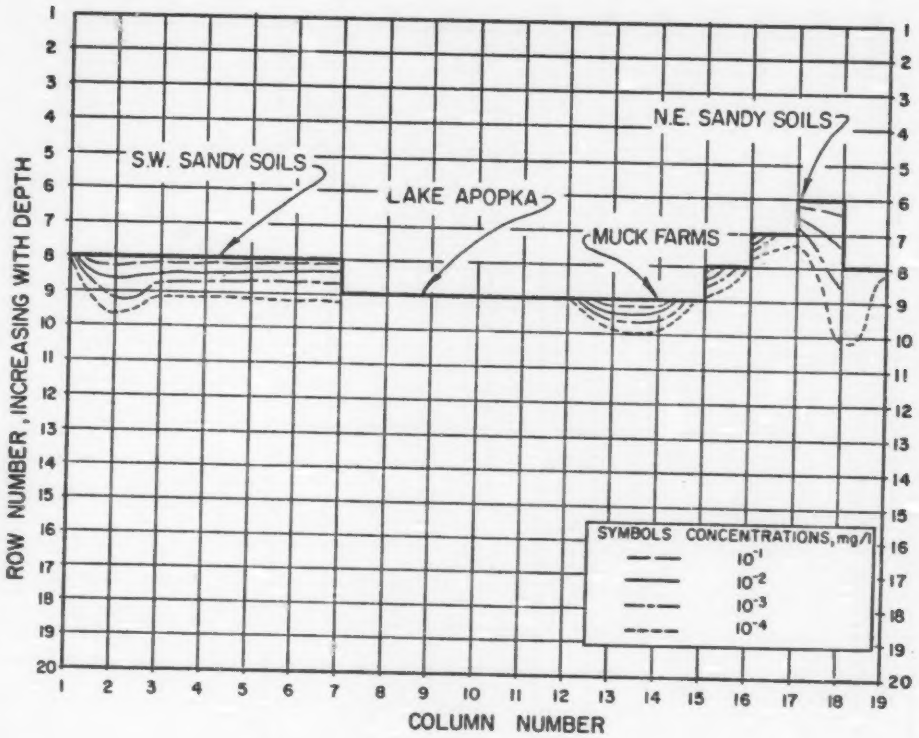


Figure 65. Predicted nitrate concentration contours in cross-section AA' (Figure 23) after one day of input.

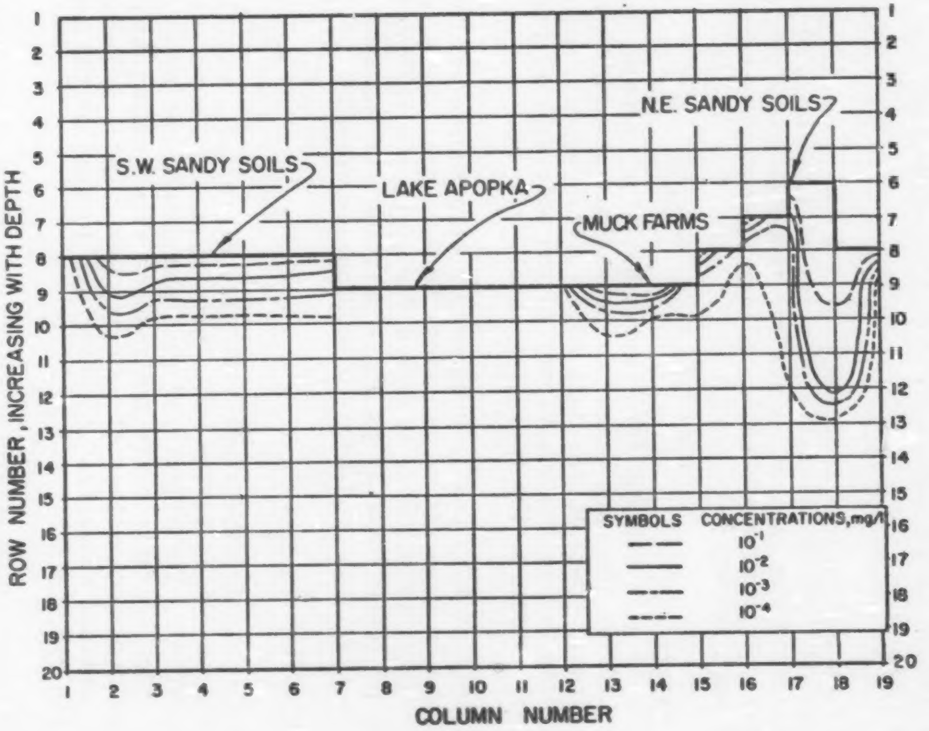


Figure 66. Predicted nitrate concentration contours in cross-section AA' (Figure 23) after 10 days of input.

SURFACE WATER

Overland Flow

To investigate the effect of extreme rainfall events on overland flow, several simulated high intensity storms were applied to a catchment in the sandy soils area (see Figure 49). The rainfall hyetographs used were multiples of that shown in Figure 49. Thus, an "intensity ratio" is defined as the ratio of hyetograph ordinates to those of Figure 49.

The results of the various runs are provided in Figure 67. The plot of peak outflows versus rainfall intensity ratio shows a steady rise with increases in the latter. A similar trend is found for the phosphorous flux. In catchments having milder slopes, phosphorous flux rates were much lower.

Receiving Waters—

In an effort to gain insight into system behavior, several trial runs were conducted for the muck farms, using various boundary conditions and assumptions. However, the lack of accurate records, especially on pumpage figures and on the efficiency of the mole drains, precluded a thorough calibration of the receiving model.

Likewise, usage of this costly program for Lake Apopka was kept to a minimum. Data on source/sink reactions between the lake water and the bottom sediments would be required for effective calibration. Also, usage of longer time steps and simulation periods would be necessary to deal with long-term eutrophication trends.

UNSATURATED ZONE

In the quality run for the sandy soil (see Figure 62), the illustration of the phenomenon of advection would have required a much longer simulation period. The effects of this phenomenon can be observed in Figure 68. Plotted therein are the results of a simulation run in which arbitrarily high values of velocity were used. At time step $n = 10$, the maximum concentration point was located at the second node from the top.

Since the predicted concentration profile in the muck soil did not agree with available data for the area, additional attention was paid to nutrient releases by the soil. For this purpose, the effects of several trial release rates were investigated in the quality model. These rates were assumed to be time-invariant and constant with depth. These assumptions were quite simplistic because the release mechanisms are likely to be numerous and sensitive to environmental factors.

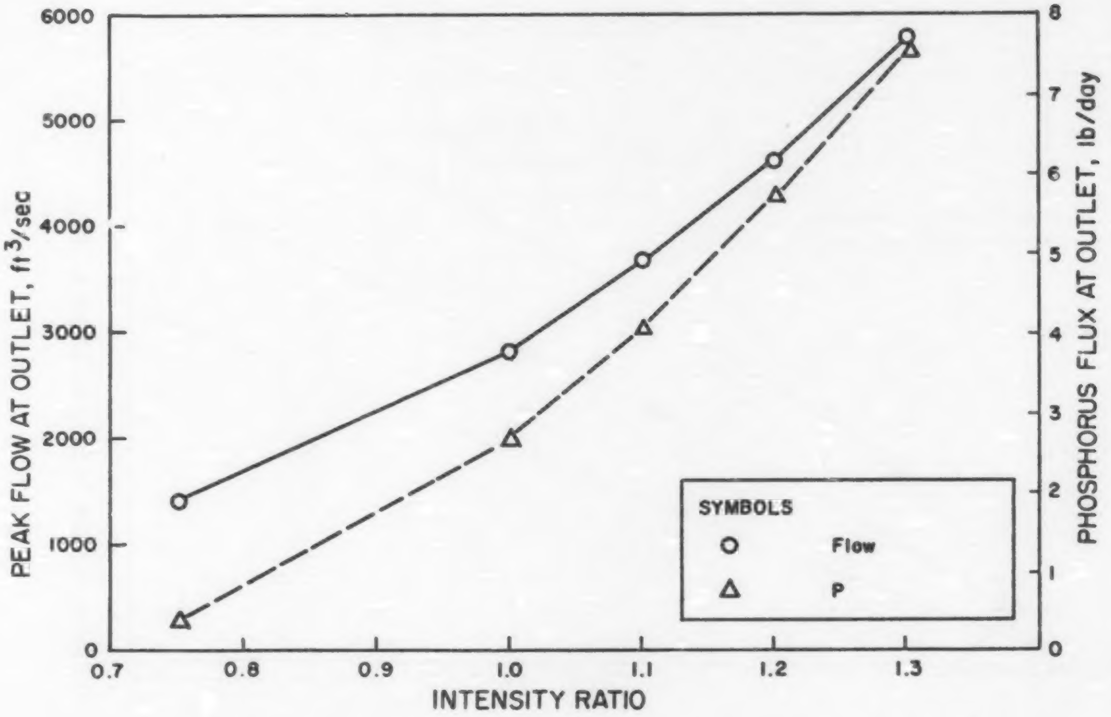


Figure 67. Predicted peak flows and peak phosphorous fluxes in catchment 1 for various rainfall intensities.

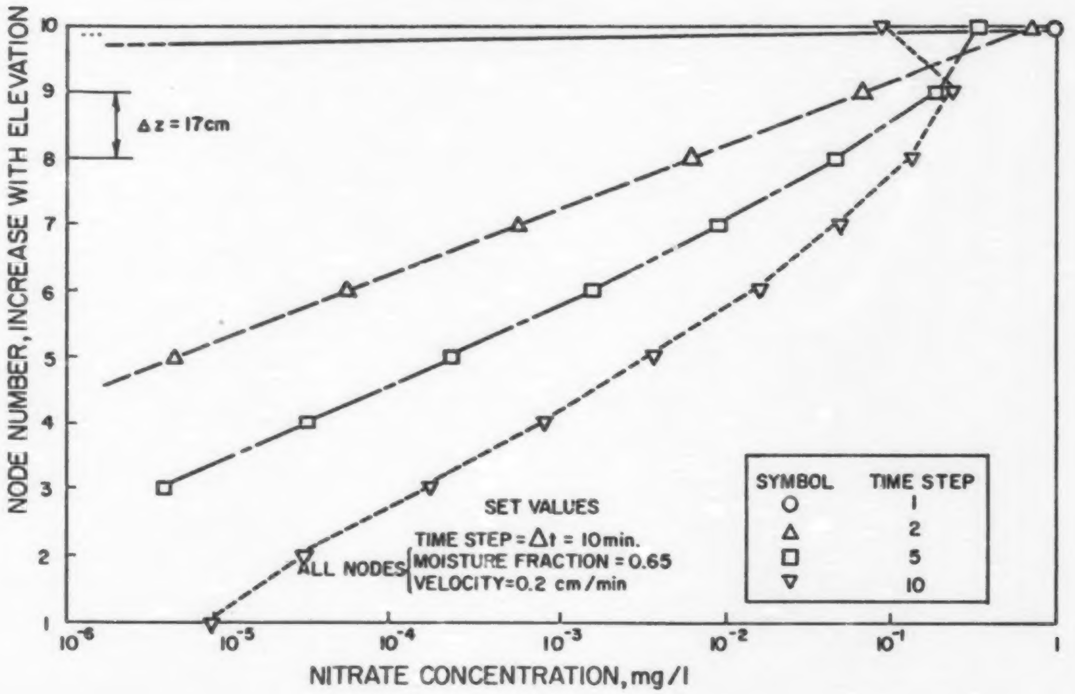


Figure 68. Predicted nitrate concentration profile for hypothetical soil under assumed high velocity conditions.

The source rate estimates used were necessarily rough. Some data on muck consolidation in the Everglades (Stephens, 1969) and on the nutrient content of muck (Heaney, Perez and Fox, 1972) were used in attempts to determine upper bounds of nutrient release (see Appendix E). The concentration profiles obtained for a given source rate are shown in Figure 69. The assumed hydrologic conditions are also indicated.

In the initial time steps, the predicted concentration profiles were fairly uniform with depth. Subsequently, the downward velocities produced profiles in which the concentrations increased with depth. For dry periods in which soils approach an equilibrium no-flow condition, the concentration profiles should be relatively uniform.

Lower values of nutrient release were used in other trial runs. Similar shapes of concentration profiles were obtained.

GROUNDWATER ZONE

In the groundwater model runs, emphasis was placed on investigating model sensitivity to changes in flow and quality boundary conditions. Preliminary computer runs indicated significant model sensitivity to permeability changes. However, an organized analysis of this latter effect was not possible within the scope of this study.

The flow boundary conditions considered were water table elevations, which fluctuate in response to rainfall and evaporation. Of specific interest was the sensitivity of groundwater recharge rates to these fluctuations. The investigation of this relationship is illustrated in Figure 70. Isolated in this figure is a portion of the groundwater cross-section considered in this study, namely, the region extending from the southwestern boundary of the basin to the vicinity of Gourd Neck Spring (see Figure 22). The analytical procedure used consisted of the following steps: (1) apply uniform increments of water table elevation (head) to the top nodes, (2) run the groundwater model for each new increment and (3) store the vertical flow velocities at the row of nodes immediately below the top row. The average velocity at these nodes was assumed to constitute the recharge rate in each case.

The computed recharge rates resulting from various water table heads are plotted in Figure 71. As expected, recharge increased with higher water tables. However, the response sensitivity was considered to be sufficiently small to allow the usage of time-average recharge rates in subsequent interfacing activities between the unsaturated zone and groundwater models. Somewhat similar response characteristics were obtained for the sandy soils area north of the muck farms.

The results shown in Figures 64, 65 and 66 indicated a downward movement of nitrate from the surface sources toward the Floridan Aquifer.

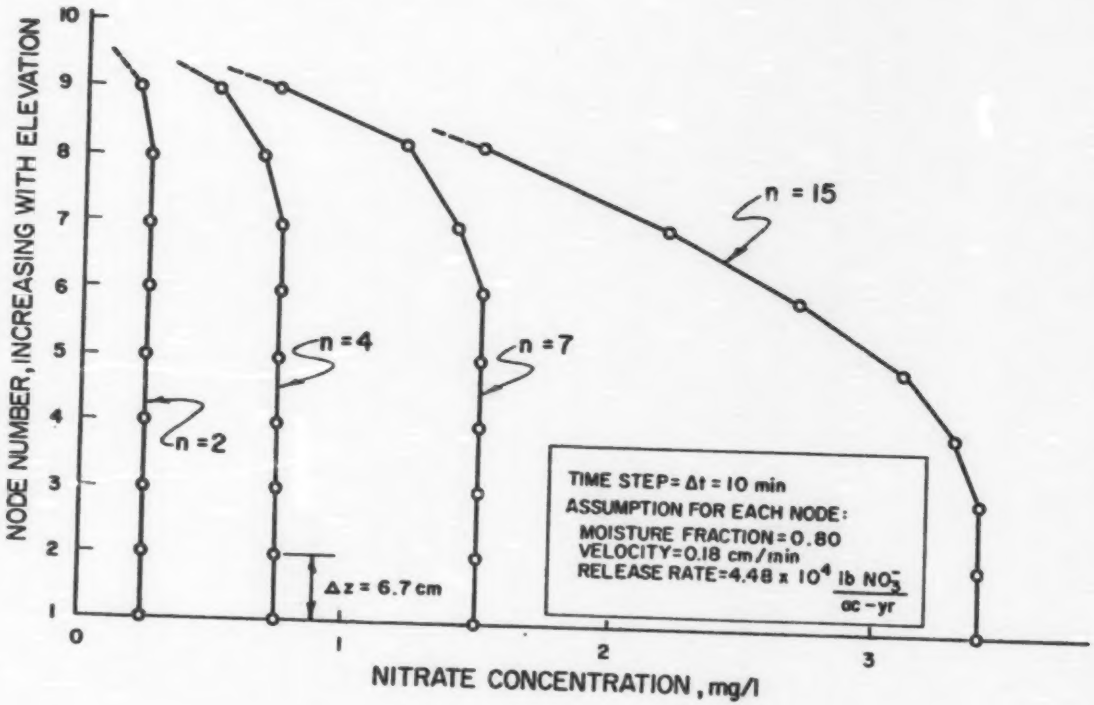


Figure 69. Predicted nitrate concentration profiles for assumed high value of release rate by muck.

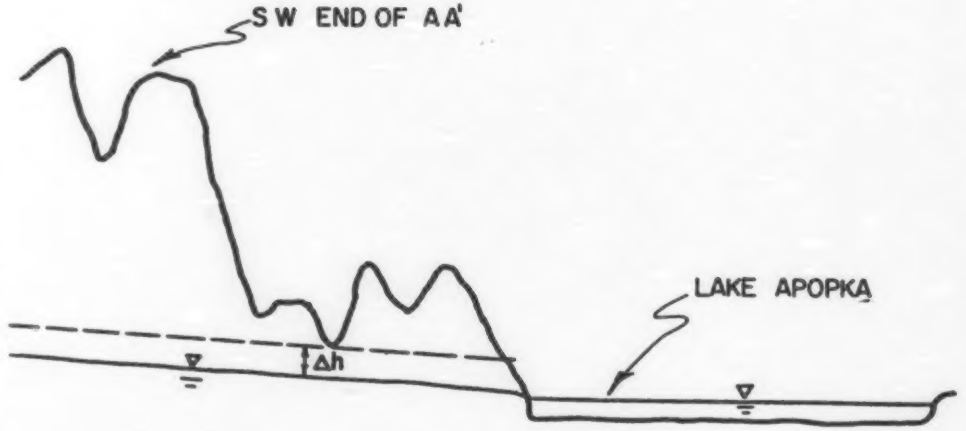

S W END OF AA'
LAKE APOPKA
Δh

Figure 70. Lateral view of a portion of cross-section AA' (Figure 23).

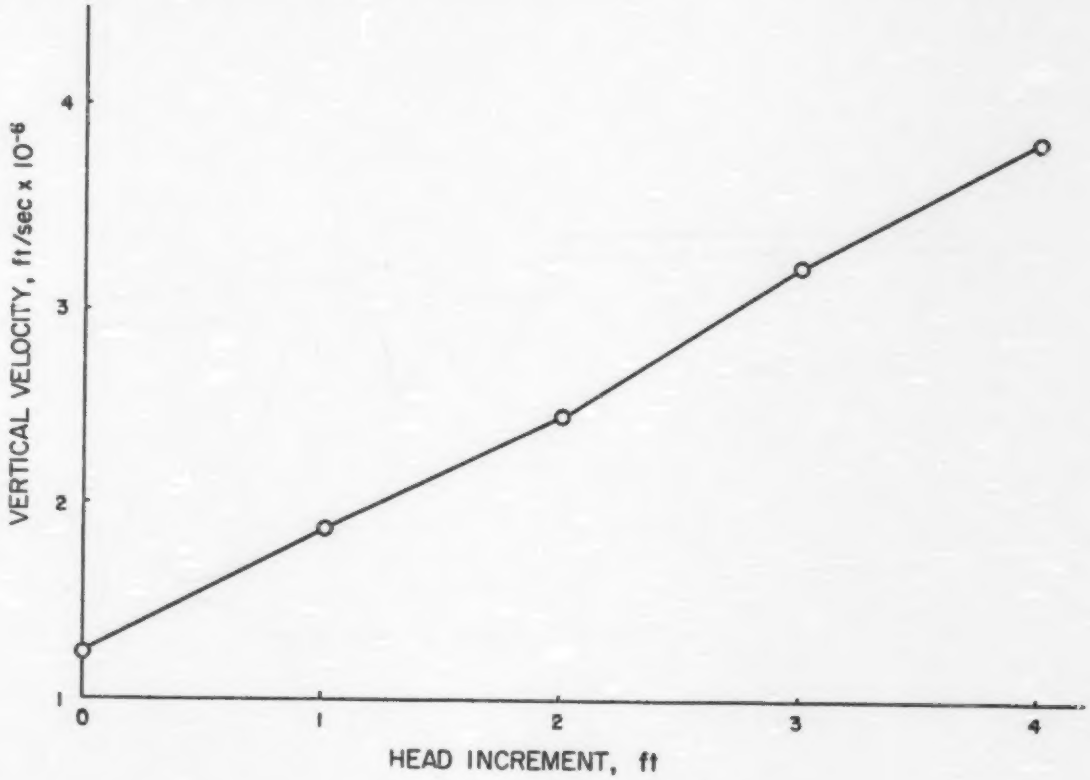


Figure 71. Predicted recharge velocities resulting from various increases in water table elevation.

Additional information was sought by extending the simulation period. The predicted contours following 68.8 days of input are given in Figure 72. In the right hand portion of the figure, the advancing high concentration (10^{-1}) front has been slowed down. This is due to the low permeability section in the vicinity (see Figure 45).

The high vertical velocities in the upper nodes of the sand formations dictated that a time step no greater than one day be used. For this reason, simulation over long time periods would have been very costly.

SUMMARY

The results obtained indicate that it is feasible to model a conjunctive surface-groundwater system. Current data limitations precluded an adequate calibration of the model. However, the formulation can be used as a guide for data collection.

While it is desirable to conduct modeling from a systems viewpoint, it appears that a close integration of the various individual programs would be premature. In their present relatively independent status, the programs are more accessible for the introduction of improvements. Also, the high computation cost and programming complexities inherent in a fully interfaced approach seem to be unwarranted in the light of data deficiencies.

SUGGESTIONS FOR FURTHER WORK

Discussed below are possible improvements that might be incorporated into the methodology and some extensions of its usage. Considered first are improvements of the individual models. Data collection and parameter optimization factors are discussed next. Finally, several comments about the study area are included. It is likely that some of these comments will be applicable to other locations.

In the formulation of improvements, a compromise must be established between accuracy and cost. The desirable position of this balance depends strongly on the nature of the study area and the planned use of the model. The numerous cost-efficiency tradeoffs can perhaps be most effectively evaluated by decision-makers, who are generally the ultimate users of models (Kisiel, 1971).

Individual Models

Surface Water Models—

Kinematic wave model— The little apparent significance of overland flow in the Lake Apopka basin and the lack of appropriate data precluded adequate verification of the kinematic wave relationships. Nevertheless, it is felt that several improvements therein should be given consideration, as follows:

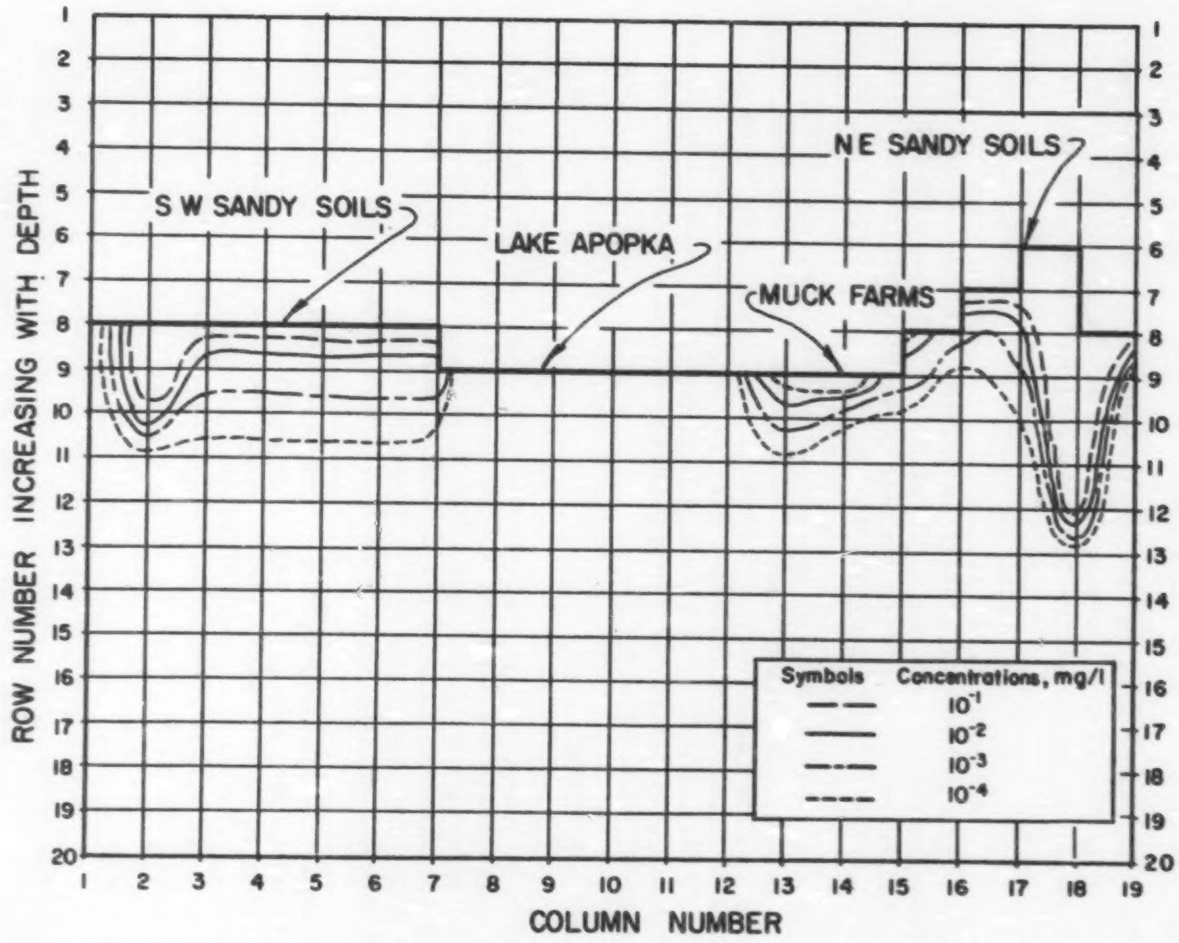


Figure 72. Predicted nitrate concentration contours in cross-section AA' (Figure 23) after 68.8 days (1656 hours) of input.

1. Allowance should be made for a given catchment to provide flows to another catchment. Recent reports from the Massachusetts Institute of Technology (Harley, Perkins and Eagleson, 1970) contain useful information on this matter.

2. A more rigorous interfacing between overland flow and flow through the unsaturated zone might be desirable. Smith and Woolhiser (1971) developed a numerical formulation for the simultaneous consideration of these two regimes. Their methodology, which is quite general, includes provision for cascading catchment planes. However, its computational costs might be relatively high.

3. Attempts should be made to account for the effects of agricultural practices in the model. As indicated by Hills (1971), the infiltration capacity of a soil depends more on treatment factors (e.g., compaction) than on its natural characteristics. In 1971, Seginer developed a model for surface drainage of cultivated fields, which gives consideration to furrows and their hydraulic characteristics. The formulation developed by the Agricultural Research Service (1971) is also quite valuable. Testing of Manning coefficient relationships for vegetated areas (Corps of Engineers, 1956) would be desirable.

4. Much remains to be accomplished in the matter of suspended solids and phosphorous fluxes in overland flow. A better representation of erosion phenomena might be obtained by utilizing a Lagrangian modeling approach, in which the path of the particles are followed as they move through the system. Additional agricultural data are required to improve estimates of phosphorous content in suspended soil particles.

Stormwater Management Model— The stormwater model offers advantages in its inherent structure for designating catchments and reading in data in an organized fashion. Its structure is also well suited for interfacing with the receiving model. However, several modifications to the formulation should be contemplated:

1. At present, the model contains calculations for hydraulic elements which are not found in agricultural areas, such as pipes and gutters. These calculations were bypassed in this study, but for more intensive use of the model it might be worthwhile to carry out a more thorough elimination and rewriting process. The same argument applies to water quality computations, such as those for biochemical oxygen demand (BOD) and coliform bacteria counts.

2. Consideration should be given to improvements regarding closer interfacing with unsaturated zone flows, accounting for agricultural practices and sediment load calculations. The same specific comments provided for the kinematic wave model apply herein.

Receiving water model— The performance of the flow portion of this model, in both the drainage canals and Lake Apopka, was satisfactory. Due to the flexibility of its link-node structure and its ability to consider various boundary conditions, the model has great applicability to practical situations. Its major drawback lies in its high computational cost. Suggested improvements lie in the area of quality calculations:

1. For a complete understanding of nutrient behavior, it would be desirable to incorporate an ecosystem model in the quality subroutines. Such models have been proposed by numerous investigators, including Chen (1969), Bloom, Levin and Raines (1969) and Chen and Orlob (1972). Since the amount of data required to calibrate an ecosystem model is rather massive, the development of a data collection strategy would appear worthwhile. In this regard, Park and Wilkerson (1971) provide insight into the interaction between statistical studies and sampling programs. In a recent paper, Moore (1972) discussed the use of filter theory in data collection, and the tradeoffs between spatial and temporal frequency in sampling.

2. Since often appreciable amounts of nutrients are contained in soil particles, it would be pertinent to devote further attention to the phenomenon of sediment transport. The consideration of this phenomenon within the receiving bodies of the Lake Apopka basin (and other agricultural basins) would appear to be of interest. In a study of cohesive soils, Partheniades (1965) concluded that erosion rates were rather independent of the concentration of suspended sediment, and arrived at several other generalizations regarding erosion and deposition factors. In 1968, Etter _et al_. discussed the importance of particle sizes and their relationship to flocculation. In addition to information contained in such studies, data are required on nutrient uptake and realease rates from sediments.

Unsaturated Zone Model—
The most important suggested improvements for this model are on the subject of water quality. Following is a list of suggestions:

1. It might be desirable to integrate this model more fully with an overland flow formulation (Smith and Woolhiser, 1971), as discussed previously.

2. There is a general scarcity of data on hydraulic conductivities under unsaturated conditions, especially for muck soils. More information on this matter would be desirable.

3. Much attention should be paid to the impact of agricultural activities on flow conditions in soils. Some of the basic relationships developed in this study for water uptake by plants could be improved in

their representation of seasonal patterns and the effects of different crops. Another possible feature to be included would be the flow of water through the voids between the plant roots and the soil. This and other features are contained in a model developed recently by the Agricultural Research Service (ARS) (1971).

4. A considerable amount of work remains to be done on the determination of source/sink rates for nutrients in soils. At present, the qualitative understanding of the mechanisms affecting these rates is very limited. It is suggested that the model developed herein be used as a guide for data collection and for verification purposes. It is also thought that the ARS model could be improved by the incorporation of water quality routines.

Groundwater Model—

It is felt that the decision to utilize a steady-state two-dimensional model, explained in previous sections, was justified in terms of cost and the accuracy desired for most agricultural situations. However, in basins where pumpage and other boundary conditions produce significant changes in piezometric conditions over time and space, the use of an unsteady-state three-dimensional formulation (Freeze, 1971) may be necessary. Most of the remaining comments deal with general approaches to model calibration:

1. In groundwater systems, it is commonplace to find that more than one set of heads and permeabilities will satisfy certain known flow conditions. This problem of indeterminacy poses serious difficulties to the calibration of both the flow and quality portions of the model. The possible use of an optimization approach to the estimation of model parameters is discussed later.

2. It appears worthwhile, on a long-range basis, to pursue the global energy approach proposed by Back and Hanshaw (1970). The success of this method, which was discussed previously, would depend on both a better understanding of energy phenomena and intensive sampling. It would seem appropriate to devote the original modeling efforts in connection with this approach to well-defined geologic systems and substances of simple chemical behavior.

3. Additional quantitative information should be obtained on source/sink reactions of nutrients in groundwater. Since agricultural phosphorous is likely to be fixed to the shallow soil zone, more attention might be devoted to anaerobic nitrogen reactions.

Data Collection and Parameter Estimation

The problem of indeterminacy, which is quite significant in groundwater models, is also present in other subsystem formulations. Thus the consideration of data collection aspects is extremely complex. Several data collection strategies have been developed whose basic objective is to minimize the variance between observed and predicted values (Matalas, 1967). However, in the modeling of a conjunctive surface-groundwater system the precise definition of an objective function is an elusive matter. This problem is due to the stepwise (flow followed by quality) nature of the predictive process, and the large number of subsystem models. In designing sampling programs, it would seem reasonable to assign higher priority to the data that are more likely to affect pollution abatement decisions. Kisiel (1971) has provided useful insight into the use of decision theory to determine the value of data.

In view of the imperfect nature of any data base, it is also worthwhile to enhance the predictive quality of models by improving the estimates of various parameters. Optimization methods for flow resistance in overland flow (Schreiber and Bender, 1972) and for permeability in groundwater (Kleinecke, 1971) are available. The latter contains restrictive assumptions such as homogeneity of the medium and the occurrence of flow in two dimensions only. Since available optimization techniques involve only flow phenomena, the development of counterparts would be required to calibrate quality processes.

The multiplicity of subsystems within any given basin suggests the use of a decomposition, rather than integrated, approach for both data collection and parameter optimization. Much remains to be accomplished on the quantitative understanding of interactions between subsystem models through boundary conditions, and on the effect of flow prediction improvements upon water quality modeling. Regarding the latter, perhaps the global energy approach suggested by Back and Hanshaw (1970) could be used to eliminate the need for the classical two-step (flow, then quality) approach.

Suggestions for the Lake Apopka Basin

Due to the current interest in the water quality of Lake Apopka and its possible restoration, it seems pertinent to summarize the main data needs and potential model uses:

1. Available data were inadequate to determine a reasonably accurate hydrologic budget of the muck farms area (Heaney, Perez and Fox, 1972). Pumpage figures are quite rough and no records are kept on the operation of the flap valves. It is suggested that better data be obtained for these flows. Groundwater flows in the area also merit further attention.

2. In the muck farms, the impact of fertilizer application appears to be less significant than that of nutrient releases by the soil. Data

leading to a better understanding of the mechanisms affecting this release would be very desirable.

3. The nitrogen contributions from the citrus groves to the groundwater system might be appreciable. However, due to the piezometric conditions, any fluxes into Lake Apopka are likely to be small. The only significant contribution to the lake could occur at Gourd Neck Spring.

4. The results of the receiving model indicate that the horizontal movement of substances in Lake Apopka is quite slow. Thus, it might be worthwhile to incorporate the phenomenon of diffusion into the model. A better quantitative understanding of source/sink reactions between the lake water and the bottom sediments would be very helpful. Research on sediment transport aspects, including particle size and scouring characteristics, should be useful. Also, the mixing effect of wind should be included. This effect might account for the fairly uniform (in the horizontal sense) pattern of nutrient concentrations in the lake.

5. Overland flow appears to be of very limited significance in the Lake Apopka basin. In future modeling efforts in this basin, it might be desirable to bypass consideration of this phenomenon, except in the case of very high intensity storms.

6. The methodology developed herein could be used as a guide for data collection in this and other basins. Following satisfactory verification, the model could also be utilized as a tool for simulating different pollution abatement measures.

SECTION X

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SECTION XI

PUBLICATIONS

Perez, A. I., W. C. Huber, J. P. Heaney and E. E. Pyatt. A Water Quality Model for a Conjunctive Surface- Groundwater System. (Presented at the Seventh American Water Resources Conference, Washington, D. C. October 1971.)

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SECTION XII

LIST OF SYMBOLS

a = constant in infiltration equation; also, constant in dispersion equation
A = infiltration parameter
A, B, C = left-hand side coefficients in tridiagonal matrix
AC, BC, CC = left-hand side coefficients in tridiagonal matrix
c = concentration; also, a subscript indicating corrected value
c^* = intermediate value of concentration
C = slope of moisture versus pressure head diagram
C_p = intrinsic permeability
d = soil particle diameter
d_e = thickness of "equivalent layer" for mole drains
D = right-hand side coefficient in tridiagonal matrix; also, dispersion coefficient
DC = right-hand side coefficient in tridiagonal matrix
D_s = distance
D_x, D_y = dispersion coefficients in x- and y-directions
e = vapor pressure
E = evaporation rate
f = infiltration rate
f_i = initial infiltration rate
f_0 = final infiltration rate
F_p = potential volume of infiltration
g = gravity

h = distance between water table and drain

i = rainfall intensity; also, cumulative infiltration

i, I = column index

i_r = rainfall excess, (rainfall less infiltration)

I_t = total infiltration; also, infiltration rate

j, J = row index

k = Shield's parameter; also, decay coefficient

K = hydraulic conductivity or permeability

K_D = dispersion coefficient

L = catchment length; also, length of drains

m = exponent constant in kinematic wave formulation ($=5/3$ for turbulent flow)

n = time step; also, Manning's roughness coefficient; also, a constant; also, a subscript indicating new value

p = subscript indicating predicted value

P = mass of pollutant; also phosphorus

P_0 = initial mass of pollutant

q = overland flow per unit width

q_s = flux of sediment

Q = flow rate; also groundwater recharge

r = nutrient release rate

R = rainfall rate; also rainfall less evaporation; also, hydraulic radius

R_t = total rainfall

R_s = distance ratio

S = source/sink; also, sorptivity; also mole drain spacing

S_b = bed slope

S_i = sink rate of nutrients from water

S_s = specific gravity

S_0 = source rate of nutrients to water

t = time

t_c = time of concentration

t_f = duration of infiltration

t_r = rainfall duration

u = nutrient uptake rate

u, v, w = velocities

v_c = critical scouring velocity

w = relaxation factor in groundwater flow calculation; also, water withdrawal rate per unit depth

W = water withdrawal rate; also, weight

x, y, z = space coordinates

y = flow depth in overland flow

y_L = flow depth at catchment outlet

z = elevation head

α = square of ratio of horizontal to vertical spacing in groundwater model; also, constant in kinematic wave overland flow computations; also, decay constant in infiltration equation

α_3, β_3 = constants in dispersion equation

γ = unit weight of water

θ = volumetric moisture content (fraction); also angle of catchment slope

ν = kinematic viscosity of water

ρ = density of water

ϕ = hydraulic head

ψ = pressure head; also, constant in sediment load calculations

τ_0 = shear stress at the stream bed

τ_{cr} = critical shear stress for erosion

A list of computer variable names is provided in the comments section at the beginning of each program.

SECTION XIII

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APPENDIX A

DETAILS OF SURFACE WATER MODELS

INTRODUCTION

Since adequate information is available on the Stormwater Management Model runoff and receiving portions (Environmental Protection Agency, 1971), the discussion on surface water models is confined to the kinematic wave overland flow formulation as described in Section IV. The mathematics of this formulation are covered thoroughly by Eagleson (1970) and, therefore, the emphasis herein is on illustrations and sample calculations. Quality computations are included. Finally, a description of the various program subroutines is provided. Consistent English units are used throughout. Metric equivalents are not given since the data are hypothetical.

SAMPLE CALCULATIONS

Catchment Geometry

The geometric characteristics of a hypothetical catchment are illustrated in Figure 73. Part (a) of this figure is a plan view of the catchment and its boundaries and assumed dimensions are indicated. A side view of the catchment is presented in part (b) on which the slope is shown.

Hydraulic Parameters

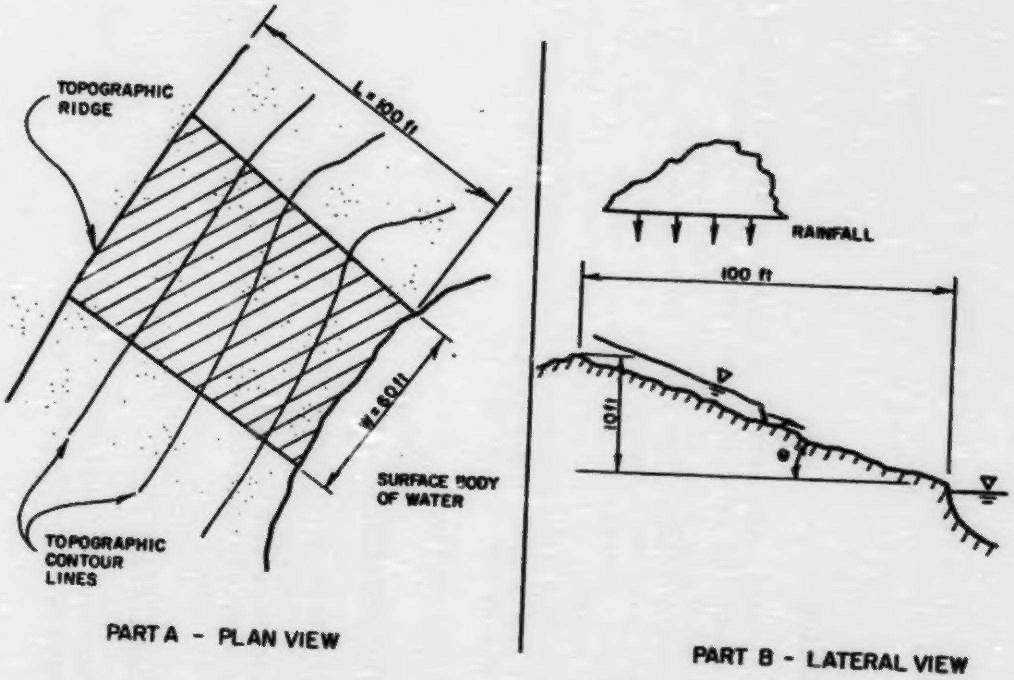
As discussed in Section IV, the flow rate at the catchment outlet can be computed from the formula:

$$q = \alpha y^m \tag{42}$$

where q = discharge per unit width, $ft^3/sec/ft$

y = depth of water, ft

α and m = constants


TOPOGRAPHIC RIDGE
L=100 ft
W=60 ft
TOPOGRAPHIC CONTOUR LINES
SURFACE BODY OF WATER
RAINFALL
100 ft
10 ft
θ

PART A - PLAN VIEW

PART B - LATERAL VIEW

Figure 73. Plan and lateral views of a hypothetical catchment.

The values of α and m vary according to whether the flow is laminar or turbulent. Eagleson has pointed out that since both flow regimes are likely to occur on vegetated surfaces, a compromise value of $m = 2$ might be used (Horton, 1938). The corresponding value of α must then be determined from field measurements.

The lack of appropriate data in the Lake Apopka basin, and possibly many other areas, precludes the statistical estimation of the parameter α. For this reason, the flow was assumed to be turbulent ($m = 5/3$). This assumption permitted the direct calculation of from:

$$\alpha = \frac{1.49}{n}(\sin\theta)^{1/2} \tag{43}$$

where θ = catchment slope angle

n = Manning roughness coefficient

In this case, the units of α are ($ft^{1/3}/sec$).

The value of n can be estimated from tabulated values for different types of land surfaces (Henderson, 1966). In vegetated areas, it appears that n varies with flow depth (U. S. Army Corps of Engineers, 1956). For simplicity, a fixed value of $n = 0.05$ is assumed for the hypothetical catchment in question.

Hydrologic Input Conditions

The hydrologic inputs required to perform the overland flow calculations are rainfall rates, infiltration rates and ponding depths. The latter two are obtained from the unsaturated zone model. The assumed values of these three variables are indicated in Figure 74. Evaporation rates are not considered.

Preliminary Calculations

Since the analytical kinematic wave formulation requires the usage of constant rainfall and infiltration inputs, preliminary calculations must be conducted to obtain time-average values for these variables. The first step is to inspect the ponding depth values to determine the time at which maximum depth occurred. This time is then assumed to be the duration, t_r, of the simplified rainstorm, which is 15 min (Figure 74).

Next, the total rainfall, R_T, is computed as follows:

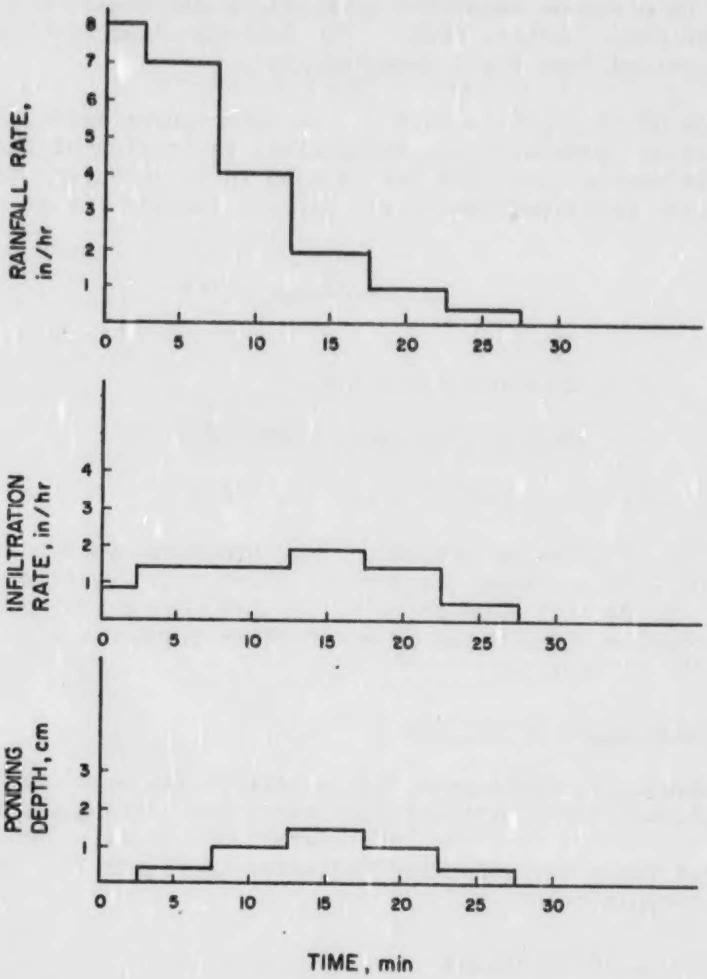


Figure 74. Hypothetical rainfall rates, infiltration rates and ponding depths used in overland flow calculations.

$$R_T = \frac{[8(2.5) + 7(5) + 4(5) + 2(5) + 1(5) + 0.5(5)]\ \frac{\text{in-min}}{\text{hr}}}{60\ \text{min/hr}} = 1.54\ \text{in}$$

and the synthetic rainfall intensity becomes

$$i = \frac{R_T}{t_r}$$

$$= 0.102\ \text{in/min} = 0.00858\ \text{ft/min} \quad \text{for } 0 \leq t \leq t_r$$

$$= 0 \quad \text{for } t > t_r$$

Turning to the infiltration calculations, it is assumed that the time at which ponding disappears constitutes the end of the infiltration process. An inspection of Figure 74 reveals that the duration of this process is $t_f = 27.5$ min.

The total amount of infiltration for that period is

$$I_T = \frac{[1(2.5) + 1.5(5) + 1.5(5) + 2(5) + 0.5(5) + 0.5(5)]\ \frac{\text{in-min}}{\text{hr}}}{60\ \text{min/hr}}$$

$$= 0.538\ \text{in}$$

Accordingly, the synthetic infiltration rates becomes

$$f = \frac{I_T}{t_f}$$

$$= 0.0196\ \text{in/min} = 0.00162\ \text{ft/min} \quad \text{for } 0 \leq t \leq t_f$$

$$= 0 \quad \text{for } t > t_f$$

Kinematic Wave Calculations

Two main cases arise in the formulation, depending on the relative values of the storm duration, t_r, and the time of concentration, t_c. The latter is computed from the formula:

$$t_c = \left(\frac{L i_*^{1-m}}{\alpha} \right)^{1/m} \qquad (44)$$

where L = catchment length, ft

i_* = rainfall excess (rainfall less infiltration in ft/min)

Substitution of the appropriate parameters in (44) yields:

$$t_c = \left(\frac{100(0.00858 - 0.00162)^{-2/3}}{\frac{1.49}{0.05}\left(\frac{10}{100}\right)^{1/2}\left(60\ \frac{\text{sec}}{\text{min}}\right)} \right)^{3/5} = \left(\frac{2800}{565}\right)^{0.6} = 2.6 \text{ min}$$

The correction factor in the denominator was necessary to convert α from $(ft^{1/3}/sec)$ to $(ft^{1/3}/min)$. For the particular catchment and hydrologic conditions in question, t_r exceeds t_c.

It is now possible to compute the depths of water, and the corresponding velocities and flows, at various times. These values are computed herein only at the catchment outlet. The calculations for the first time step (t = 5 min) are given below.

The equations used to obtain the flow depth are

$$y_L = (i - f)t \qquad 0 \le t \le t_c \qquad (45)$$

$$y_L = (i - f)t_c \qquad t_c \le t \le t_r \qquad (46)$$

A more complex relationship must be used for the case $t > t_r$. Since in this case $t_c \le t \le t_r$, the depth becomes

$$y_L = (0.00696)(2.6) = 0.0181 \text{ ft}$$

The corresponding velocity is

$$v = \alpha y^{m-1} = (9.42)(0.0181)^{0.66} = 0.705 \text{ ft/sec}$$

and the flow per unit width becomes

$$q = \alpha y^{m} = vy = 0.01275 \text{ ft}^3\text{/sec/ft.}$$

Multiplying this unit flow by the width (ft), the resulting catchment outflow is

$$Q = qw = (0.01275)(60) = 0.765 \text{ ft}^3\text{/sec.}$$

Sediment Load Calculations

The sediment transport formula used in this study is that developed by duBoys (Einstein, 1964):

$$q_s = \psi \frac{\tau_o}{\gamma}\left(\frac{\tau_o}{\gamma} - \frac{\tau_{cr}}{\gamma}\right) \tag{47}$$

where q_s = flux of sediment, lb/sec/ft of width

ψ = a constant for a given bed composition

τ_o = bed shear stress, lb/ft^2

τ_{cr} = critical shear stress, lb/ft^2

γ = unit weight of water, lb/ft^3

The bed shear stress can, in turn, be expressed as:

$$\tau_o = \gamma y S_b \tag{48}$$

where y = flow depth, ft

S_b = slope of the bed

Substitution of equation (48) into (47) yields

$$q_s = \psi y S_b \left(y S_b - \frac{\tau_{cr}}{\gamma} \right) \qquad (49)$$

which is the actual expression utilized herein. Values of ψ and τ_{cr} are tabulated (Einstein, 1964) for various grain sizes.

Assuming that the soil in the hypothetical catchment is fine sand, the sediment load at the first time step (t = 5 min) is:

$$q_s = (5.23 \times 10^5)(1.81 \times 10^{-2})(10^{-1}) \left(1.81 \times 10^{-3} - \frac{1.62 \times 10^{-2}}{62.4} \right)$$

$$= 1.47 \text{ lb/sec/ft}$$

Thus, the total catchment load becomes

$$Q_s = wq_s = 88.3 \text{ lb/sec.}$$

The calculations on the nitrogen and phosphorous fractions in the sediment load are shown in Appendix E.

PROGRAM DESCRIPTION

The kinematic wave overland flow program is composed of a main program (MAIN) and several subroutines, AVE, WAVE, RECV, HIDUR, LODUR, RQUAL and WRIT. All these subroutines are involved in quantity computations, with the exception of RQUAL and WRIT. The former handles water quality computations and the latter writes out the overall results.

Main Program

The first task of MAIN is to read in the necessary hydrologic, geometric and quality data. Included among the geometric information is the numbering system that connects the catchments with the receiving elements.

Following the data input, MAIN calls subroutines AVE, WAVE, RECV, RQUAL and WRIT, in that order. Subroutine AVE performs the averaging computations for rainfall, evaporation and infiltration, and thus prepares these data for use in the kinematic wave calculations. The task of WAVE is to carry out these calculations for all catchments and time steps. It ultimately computes flows into the receiving elements. Subroutine RECV then computes the total flows into each receiving element from all its feeder catchments. The functions of RQUAL and WRIT were explained above.

Subroutine AVE

This subroutine determines the mean values of infiltration and rainfall for the time period considered. The stepwise procedure used to obtain these values, discussed below, are also shown in Figure 75 and 76.

Beginning with infiltration, AVE first determines the time step after which this process no longer occurs. The method used is to scan the infiltration results from the unsaturated zone program and establish when the ponding depth becomes zero. The time interval corresponding to this event is considered to constitute the end of the infiltration process. The scanning process described above is illustrated as Step 1 in Figure 75.

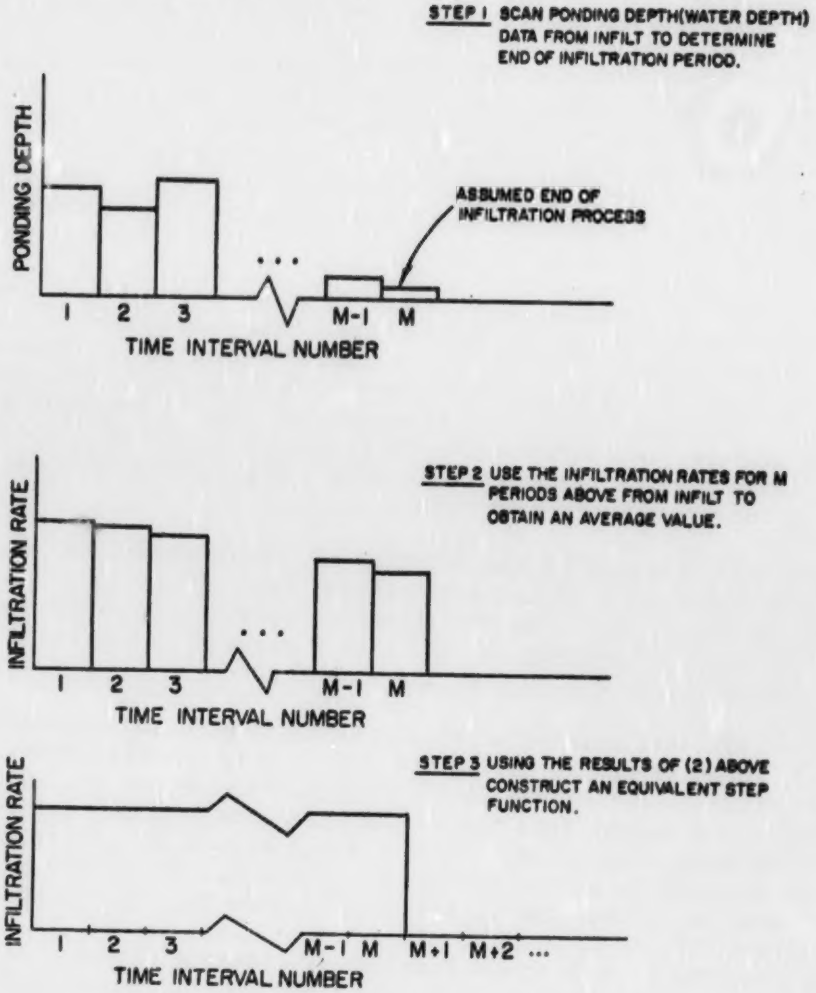
In actual practice the runoff process will probably produce a zero ponding depth condition at an earlier time than that obtained from the above scanning method. The reason is that the unsaturated zone model assumes a laterally stagnant, non-dynamic, ponding situation. Nevertheless, it is thought that the approximation used is adequate for the modeling of rural watersheds. In the future, one method to obtain more accurate results might be to interface the infiltration and overland flow models at every time step.

Following determination of the duration of infiltration, AVE computes the time-average value of the infiltration rate. This calculation is depicted as Step 2 in Figure 75. Finally, updated values of the infiltration rate are stored for all the time intervals in the study period, in the manner shown in Step 3 of the same figure.

Subroutine AVE then considers the rainfall process, and converts the original irregular-shaped hyetograph into a step function containing the same total amount of rainfall. This conversion process is begun by scanning the output from the unsaturated zone program, determining the time at which the maximum ponding depth occurs and arbitrarily setting the duration of the synthetic storm equal to the above time. This process is illustrated in Step 1 of Figure 76. The subroutine then computes the total rainfall from the original record, as shown in Step 2 of the same figure. Finally, it constructs a synthetic step function hyetograph (Step 3) using the duration, t_r, determined above.

Subroutine WAVE

To better represent the overland flow process, it is desirable to apply the kinematic wave relationships not only at each catchment outlet, but also at several points along the length of the catchment. For this



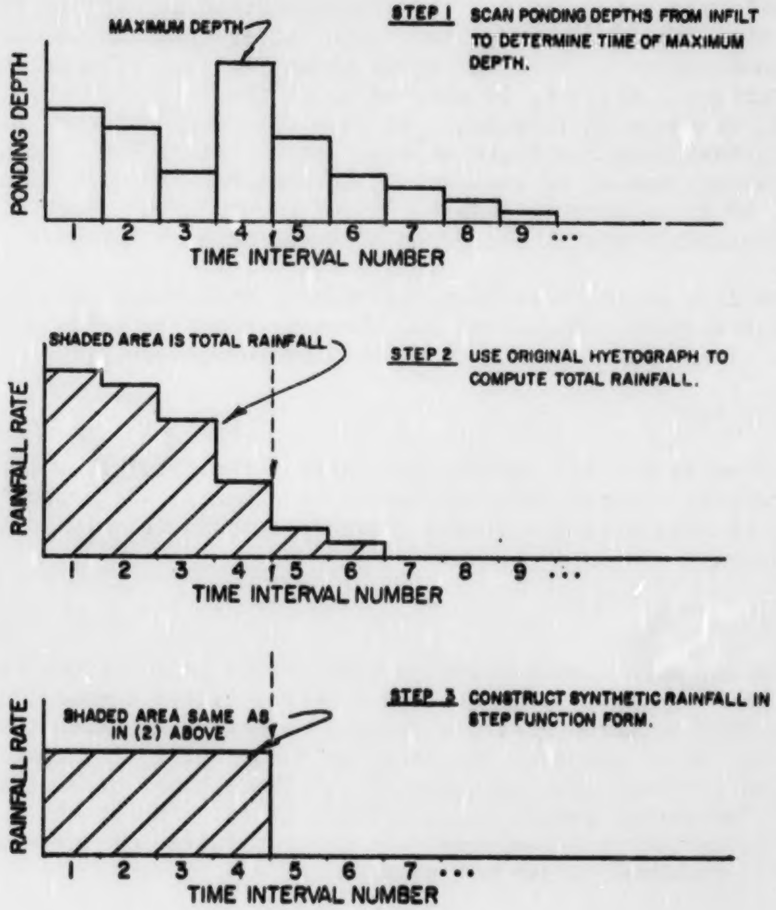
PONDING DEPTH
ASSUMED END OF INFILTRATION PROCESS
...
1
2
3
M-1
M
TIME INTERVAL NUMBER
INFILTRATION RATE
...
1
2
3
M-1
M
TIME INTERVAL NUMBER
INFILTRATION RATE
1
2
3
M-1
M
M+1
M+2 ...
TIME INTERVAL NUMBER

STEP 1 SCAN PONDING DEPTH(WATER DEPTH) DATA FROM INFILT TO DETERMINE END OF INFILTRATION PERIOD.

STEP 2 USE THE INFILTRATION RATES FOR M PERIODS ABOVE FROM INFILT TO OBTAIN AN AVERAGE VALUE.

STEP 3 USING THE RESULTS OF (2) ABOVE CONSTRUCT AN EQUIVALENT STEP FUNCTION.

Figure 75. Graphical representation of computational steps in subroutine AVE involving infiltration.


MAXIMUM DEPTH
PONDING DEPTH
1 2 3 4 5 6 7 8 9 ...
TIME INTERVAL NUMBER
SHADED AREA IS TOTAL RAINFALL
RAINFALL RATE
1 2 3 4 5 6 7 8 9 ...
TIME INTERVAL NUMBER
SHADED AREA SAME AS
IN (2) ABOVE
RAINFALL RATE
1 2 3 4 5 6 7 ...
TIME INTERVAL NUMBER

STEP 1 SCAN PONDING DEPTHS FROM INFILT TO DETERMINE TIME OF MAXIMUM DEPTH.

STEP 2 USE ORIGINAL HYETOGRAPH TO COMPUTE TOTAL RAINFALL.

STEP 3 CONSTRUCT SYNTHETIC RAINFALL IN STEP FUNCTION FORM.

Figure 76. Graphical representation of computations in subroutine AVE involving rainfall.

purpose each catchment is divided into a given number of intervals, and the formulation is applied to the downstream end of each interval. This division process is illustrated in Figure 77. In this study, only one interval, comprising the entire catchment, was considered. This was acceptable because of the small size of each catchment.

The type of formulas used at each catchment location largely depends on the relative values of t_r, the storm duration as defined in AVE, and t_c, the time of concentration. The latter term can be defined as the maximum amount of time during which an increase of depth can occur on the surface. While t_r is assumed to be the same throughout the basin, t_c varies with location. At each time step and each catchment interval, WAVE compares these values. If the storm has a relatively high duration, namely t_r exceeds t_c, subroutine HIDUR is called. Conversely, if t_c is greater than t_r, LODUR is utilized. Each of these two subroutines computes the depth of water at each catchment location.

After the flow depths have been determined, WAVE proceeds to calculate their corresponding velocities and flows by means of equations (7) and (6). These values are then stored for future use.

Subroutine RECV

At each time step, this subroutine computes the total flow entering each receiving element from its feeder catchments. To accomplish this purpose, it considers the stored flows corresponding only to the downstream interval in each catchment.

Subroutine HIDUR

The kinematic wave computations carried out in this subroutine correspond to the case $t_r > t_c$ as mentioned above. These computations branch out according to three possible cases. To determine which particular case holds, HIDUR compares the relative values of t, the time corresponding to the time step in question, to three other parameters: t_c, t_r and t_i. The latter parameter is defined as the time at which the depth, y, at a given location vanishes. At the conclusion of these calculations, control is returned to subroutine WAVE.

Subroutine LODUR

This subroutine is utilized in a relatively low duration situation; namely, $t_r < t_c$. The computations herein are broken down into three classes, depending on the relative values of t_i, defined above, and t_p, which represent the time at which the depth begins to decrease. Each one of these three cases is in turn divided into three sub-cases. As in HIDUR, control is returned to WAVE dollowing completion of the computations.

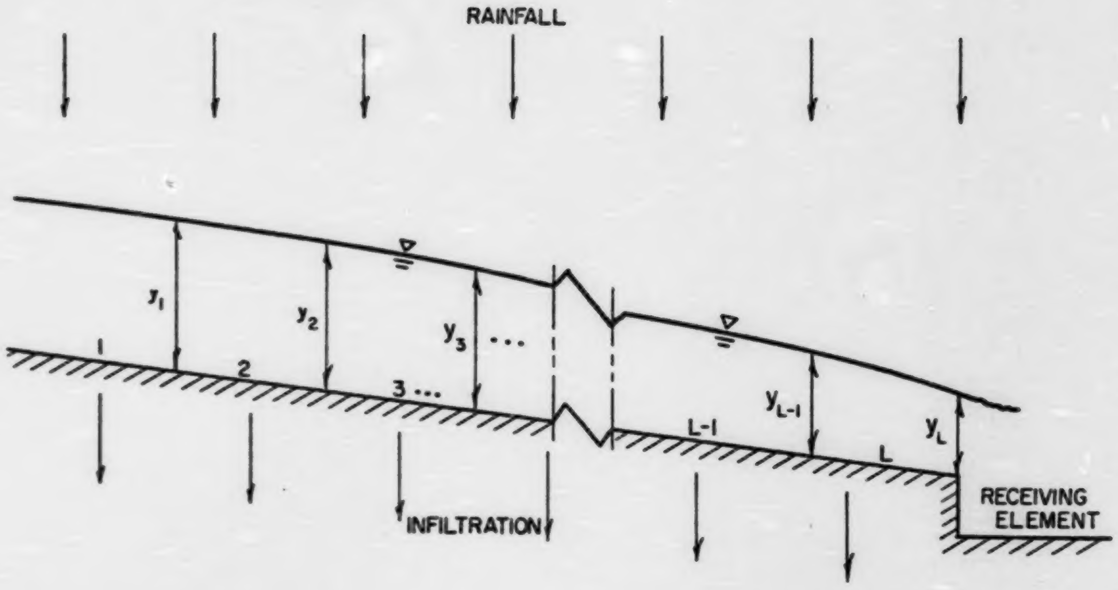

RAINFALL
y_1
y_2
y_3 ...
1
2
3 ...
INFILTRATION
y_{L-1}
y_L
L-1
L
RECEIVING ELEMENT

Figure 77. Lateral view of overland flow situation, indicating catchment divisions.

Subroutine RQUAL

This subroutine utilizes the duBoys sediment transport equation (Einstein, 1964) to compute the suspended solids fluxes at the catchment outlets. It also calculates the nitrogen and phosphorous fluxes at the outlets.

Subroutine WRIT

After subroutine RQUAL has completed its calculations, subroutine WRIT is called to print out the results obtained. The most important results are the flows and concentrations at the various catchments, and the total inputs to the receiving elements.

APPENDIX B

DETAILS OF UNSATURATED ZONE MODEL

INTRODUCTION

The first item to be discussed is the derivation of coefficients used in the matrix solutions of both the flow and quality portions of the unsaturated zone model as developed in Section V. Subsequently, sample calculations are provided for one time step. Finally, a discussion of the various subroutines is given.

DERIVATION OF COEFFICIENTS

Flow Model

The basic link-node structure used in a given soil profile is shown in Figure 78. Also indicated therein are the boundary conditions at the top and bottom of the profile.

The flow governing equation used in this study was that developed by Freeze (1969), with an additional sink term:

$$C(\psi)\frac{\partial\psi}{\partial t} + S = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right] \qquad (50)$$

where ψ = pressure head, cm

$C(\psi)$ = slope of the moisture versus pressure head curve, 1/cm

t = time, min

S = sink, 1/min

z = elevation, cm

$K(\psi)$ = hydraulic conductivity, cm/min

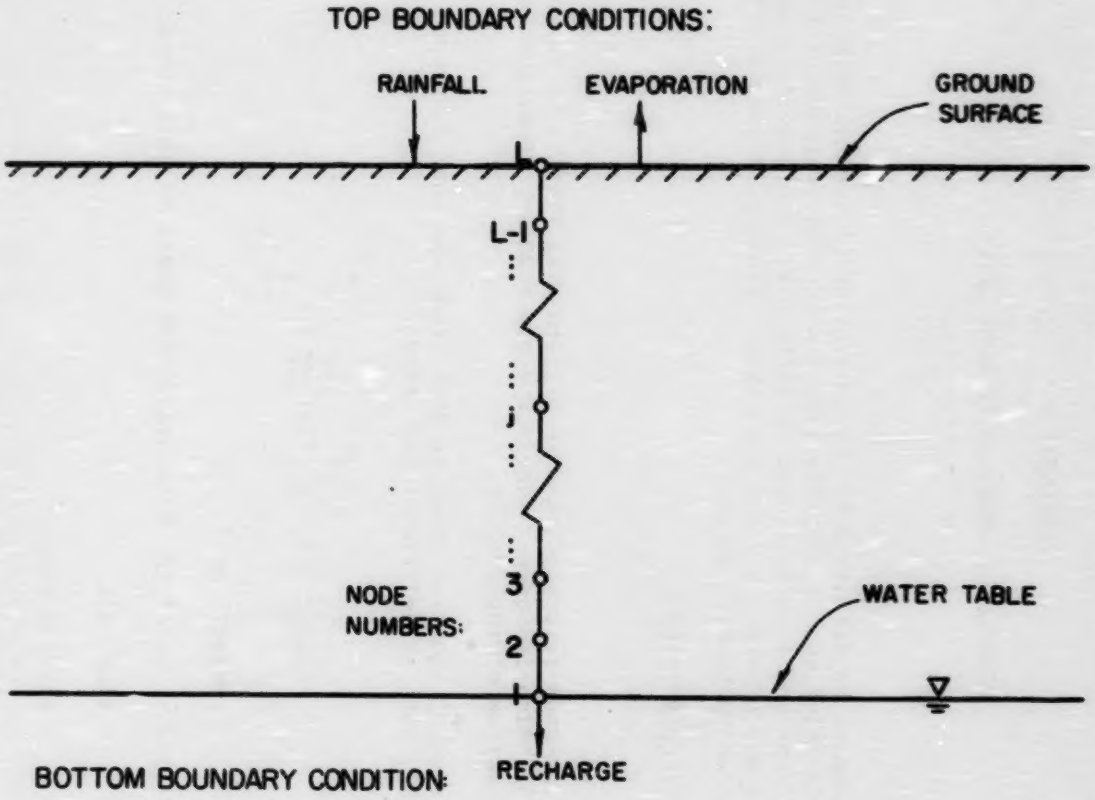

TOP BOUNDARY CONDITIONS:
RAINFALL
EVAPORATION
GROUND SURFACE
L
L-1
j
3
2
1
NODE NUMBERS:
WATER TABLE
BOTTOM BOUNDARY CONDITION:
RECHARGE

Figure 78. Illustration of unsaturated zone profile, showing nodes and boundary conditions.

The sink term above includes withdrawals by plants and artificial drains. Its usage is illustrated in Appendix E.

Interior Node—
The finite-difference expression corresponding to equation (50), written for an interior node ($1 < j < L$), is:

$$C\left(\psi_{III}\right)\left[\frac{\left(\psi_j^n - \psi_j^{n-1}\right)}{\Delta t}\right] + S_j^n$$

$$= \frac{1}{\Delta z}\left\{K(\psi_I)\left[1 + \frac{1}{2\Delta z}\left(\psi_{j+1}^{n-1} + \psi_{j+1}^{n} - \psi_j^{n-1} - \psi_j^n\right)\right]\right\} -$$

$$\frac{1}{\Delta z}\left\{K(\psi_{II})\left[1 + \frac{1}{2\Delta z}\left(\psi_j^{n-1} + \psi_j^n - \psi_{j-1}^{n-1} - \psi_{j-1}^n\right)\right]\right\} \qquad (51)$$

in which the subscripts denote the node and the superscripts the time step. The expressions for ψ_I, ψ_{II}, and ψ_{III} are the following:

$$\psi_I = \left(\psi_j^{n-1} + \psi_{j+1}^{n-1} + \psi_{j+1}^n + \psi_j^n\right)\Big/4 \qquad (52)$$

$$\psi_{II} = \left(\psi_{j-1}^{n-1} + \psi_j^{n-1} + \psi_j^n + \psi_{j-1}^n\right)\Big/4 \qquad (53)$$

$$\psi_{III} = \left(\psi_j^{n-1} + \psi_j^n\right)\Big/2 \qquad (54)$$

These expressions are valid only for $n > 2$. Otherwise, the definitions provided by Rubin and Steinhart (1963) should be used.

Since the flow governing equation form desired is:

$$-C_j\psi_{j-1}^n + B_j\psi_j^n - A_j\psi_{j+1}^n = D_j \tag{55}$$

it becomes necessary to regroup terms in equation (51). Expanding first, the following equation is obtained:

$$C(\psi_{III})\psi_j^n\Delta z - C(\psi_{III})\psi_j^{n-1} + S_j^n\Delta z$$

$$= K(\psi_I) + \frac{K(\psi_I)\psi_{j+1}^{n-1}}{2\Delta z} + \frac{K(\psi_I)\psi_{j+1}^n}{2\Delta z} - \frac{K(\psi_I)\psi_j^{n-1}}{2\Delta z} - \frac{K(\psi_I)\psi_j^n}{2\Delta z}$$

$$- K(\psi_{II}) - \frac{K(\psi_{II})\psi_j^{n-1}}{2\Delta z} - \frac{K(\psi_{II})\psi_j^n}{2\Delta z} + \frac{K(\psi_{II})\psi_{j-1}^{n-1}}{2\Delta z} + \frac{K(\psi_{II})\psi_{j-1}^n}{2\Delta z} \tag{56}$$

Rearranging terms and multiplying both sides by (-1), the expression becomes

$$-\left[\frac{K(\psi_I)}{2\Delta z}\right]\psi_{j+1}^n + \left[\frac{K(\psi_I)}{2\Delta z} + \frac{K(\psi_{II})}{2\Delta z} + \frac{C(\psi_{III})\Delta z}{\Delta t}\right]\psi_j^n - \left[\frac{K(\psi_{II})}{2\Delta z}\right]\psi_{j-1}^n$$

$$= \left[\frac{K(\psi_I)}{2\Delta z}\right]\psi_{j+1}^{n-1} + \left[\frac{C(\psi_{III})\Delta z}{\Delta t} - \frac{K(\psi_I)}{2\Delta z} - \frac{K(\psi_{II})}{2\Delta z}\right]\psi_j^{n-1} + \left[\frac{K(\psi_{II})}{2\Delta z}\right]\psi_{j-1}^{n-1}$$

$$+ K(\psi_I) - K(\psi_{II}) - S_j^n\Delta z \tag{57}$$

Note that the terms on the right-hand side are known quantities.

Comparing equation (57) to (55) it follows that:

$$A_j^n = \frac{K(\psi_I)}{2\Delta z} \tag{58}$$

$$B_j^n = \frac{K(\psi_I)}{2\Delta z} + \frac{K(\psi_{II})}{2\Delta z} + \frac{C(\psi_{III})\Delta z}{\Delta t} \tag{59}$$

$$C_j^n = \frac{K(\psi_{II})}{2\Delta z} \tag{60}$$

$$D_j^n = A_j^n \psi_{j+1}^{n-1} + \left[\frac{C(\psi_{III})\Delta z}{\Delta t} - \frac{K(\psi_I)}{2\Delta z} - \frac{K(\psi_{II})}{2\Delta z}\right]\psi_j^{n-1} + C_j^n \psi_{j-1}^{n-1}$$

$$+ K(\psi_I) - K(\psi_{II}) - S_j^n \Delta z \tag{61}$$

The expressions for the four coefficients above are valid for any interior node. However, the expressions for the top and bottom nodes constitute special cases.

Top Node—
The boundary condition at the ground surface ($j = L$) is (Freeze, 1969):

$$\frac{\partial \psi}{\partial z} = \left[\frac{R}{K(\psi)}\right] - 1 \tag{62}$$

where R = net rainfall infiltration (rainfall less evaporation), cm/min

If a sink term is included, equation (62) can be rewritten as:

$$R - S(\Delta z/2) = K\left(\psi_{L-\frac{1}{2}}^{n-\frac{1}{2}}\right)\frac{\partial \phi}{\partial z} \tag{63}$$

where $\phi = \psi + z$

The finite-difference expression for (63), after some rearranging, becomes

$$\psi_L^n - \psi_{L-1}^n = \frac{R\Delta z\,.}{K\left(\psi_{L-\frac{1}{2}}^{n-\frac{1}{2}}\right)} - z_L + z_{L-1} - \frac{S_L^n(\Delta z/2)\Delta z}{K\left(\psi_{L-\frac{1}{2}}^{n-\frac{1}{2}}\right)} \tag{64}$$

Thus, the coefficient expressions become

$$A_L^n = 0 \tag{65}$$

$$B_L^n = C_L^n = 1 \tag{66}$$

$$D_L^n = \frac{R\Delta z}{K\left(\psi_{L-\frac{1}{2}}^{n-\frac{1}{2}}\right)} - z_L + z_{L-1} - \frac{S_L^n(\Delta z/2)\Delta z}{K\left(\psi_{L-\frac{1}{2}}^{n-\frac{1}{2}}\right)} \tag{67}$$

Bottom Node—

The boundary condition at the bottom node ($j = 1$) can be written as:

$$K\left(\psi_{1\frac{1}{2}}^{n-\frac{1}{2}}\right)\frac{\partial\phi}{\partial z} = Q + S_j^n(\Delta z/2) \tag{68}$$

Where Q = groundwater recharge (positive downward), cm/min

After some manipulations, the following expression is obtained:

$$-\psi_2 + \psi_1 = -\frac{Q\Delta z}{K\left(\psi_{1\frac{1}{2}}^{n-\frac{1}{2}}\right)} - z_1 + z_2 - \frac{S_1(\Delta z/2)\Delta z}{K\left(\psi_{1\frac{1}{2}}^{n-\frac{1}{2}}\right)} \tag{69}$$

It follows that the coefficient expressions are:

$$A_1^n = B_1^n = 1 \tag{70}$$

$$C_1^n = 0 \tag{71}$$

$$D_1^n = -\frac{Q\Delta z}{K\left(\psi_{1\frac{1}{2}}^{n-\frac{1}{2}}\right)} - z_1 + z_2 - \frac{S_1(\Delta z/2)\Delta z}{K\left(\psi_{1\frac{1}{2}}^{n-\frac{1}{2}}\right)} \tag{72}$$

Quality Model

The quality governing equation consists of a convective-dispersion formulation with provision for source/sink reactions:

$$\frac{\partial}{\partial t}(\theta c) = -v\frac{\partial c}{\partial z} + K_D(v)\frac{\partial^2 c}{\partial z^2} + S_o - S_i \tag{73}$$

where t = time, min

θ = moisture fraction, cm/cm

c = concentration, mg/l

v = velocity (positive upward), cm/min

z = elevation, cm

K_D = dispersion coefficient, cm^2/min

S_o = source, mg/l/min

S_i = sink, mg/l/min

Since the flow through the soil will be downward following rainstorms, it is convenient to re-define the velocity sign convention as positive downward. The resulting expression becomes:

$$c\frac{\partial\theta}{\partial t} + \theta\frac{\partial c}{\partial t} = v\frac{\partial c}{\partial z} + K_D(v)\,\frac{\partial^2 c}{\partial z^2} + S_o - S_i \tag{74}$$

The computation of source/sink terms is illustrated in Appendix E. To solve (74) numerically, it is necessary to regroup its terms and obtain an expression of the form:

$$-\,(CC)_j^n c_{j-1}^n + (BC)_j^n c_j^n - (AB)_j^n c_{j+1}^n = (DC)_j^n \tag{75}$$

The expressions for coefficients AC, BC, CC and DC are derived below.

Interior Node—
For an interior node (1 < j < L), equation 74 can be written in finite-difference form as:

$$c_j^n\frac{\left(\theta_j^n - \theta_j^{n-1}\right)}{\Delta t} + \theta_j^n\,\frac{\left(c_j^n - c_j^{n-1}\right)}{\Delta t}$$

$$= v_j^n\frac{\left(c_{j+1}^n - c_{j-1}^n\right)}{2\Delta z} + K_{D_j}^{\ n}\frac{\left(c_{j+1}^n - 2c_j^n + c_{j-1}^n\right)}{(\Delta z)^2} + S_{o_j}^{\ n} - S_{i_j}^{\ n} \tag{76}$$

After some algebra, the following expressions are obtained

$$AD_j^n = \frac{v_j^n}{2\Delta z} + \frac{K_{D_j}^{\ n}}{(\Delta z)^2} \tag{77}$$

$$BC_j^n = \frac{\theta_j^n - \theta_j^{n-1}}{\Delta t} + \frac{\theta_j^n}{\Delta t} + \frac{2K_{D_j}^{\ n}}{(\Delta z)^2} \tag{78}$$

$$CC_j^n = -\,\frac{v_j^n}{2\Delta z} + \frac{K_{D_j}^{\ n}}{(\Delta z)^2} \tag{79}$$

$$DC_j^n = S_{o_j}^n - S_{i_j}^n + \frac{\theta_j^n c_j^{n-1}}{\Delta t} \quad (80)$$

Top Node—
At the uppermost node (j = L), the dispersion and source/sink terms are neglected. Its concentration at the first time step is set, and its value at subsequent steps is computed as follows:

1. Determine the distance, D_s, that the substance traveled between the current and the previous time step.

$$D_s = v_L^{n-1}\Delta t \quad (81)$$

2. Calculate the ratio, R_s, of this distance to the midpoint distance between the two upper nodes

$$R_s = \frac{v_L^{n-1}\Delta t}{(\Delta z/2)} \quad (82)$$

3. Develop a mass-balance relationship involving the current and previous time steps:

$$\theta_L^n c_L^n = \theta_L^{n-1} - \theta_L^{n-1} c_L^{n-1} R_s \quad (83)$$

4. Substitute (82) into (83) and rearrange terms, to yield:

$$c_L^n = \frac{\theta_L^{n-1}}{\theta_L^n} c_L^{n-1}\left(1 - \frac{v_L^{n-1}\Delta t}{\Delta z/2}\right) \quad (84)$$

Thus, coefficients AC, BC, CC and DC are not used explicitly to compute the concentrations at the top node.

Bottom node—
Due to the absence of two adjacent nodes, required to evaluate a second derivative, the dispersion term is not considered at the bottom node (j = 1). The finite-difference form of equation (74) at this location is:

$$c_1^n \frac{\left(\theta_1^n - \theta_1^{n-1}\right)}{\Delta t} + \theta_1^n \frac{\left(c_1^n - c_1^{n-1}\right)}{\Delta t} = v_1^n \frac{\left(c_2^n - c_1^n\right)}{\Delta} + S_{o_1}^{\,n} - S_{i_1} \qquad (85)$$

The resulting expressions for the coefficients, after regrouping of terms,

$$A_1^n = \frac{v_1^n}{\Delta z} \qquad (86)$$

$$B_1^n = \left(\frac{\theta_1^n - \theta_1^{n-1}}{\Delta t}\right) + \frac{\theta_1^n}{\Delta t} + \frac{v_1^n}{\Delta z} \qquad (87)$$

$$C_1^n = 0 \qquad (88)$$

$$D_1^n = \frac{\theta_1 c_1^{n-1}}{\Delta t} + S_{o_1}^{\,n} - S_{i_1}^{\,n} \qquad (89)$$

Discussion of Dispersion Equation—
The expression used to compute the dispersion coefficient was derived by Hoopes and Harleman (1965) for sands based on laboratory experiments. It is unlikely to be generally applicable, but was useful for this study. The expression is:

$$K_D = (\nu\alpha_3)\frac{v(C_p)^{\frac{1}{2}}\beta_3}{\nu} \qquad (90)$$

where ν = kinematic viscosity of water, cm^2/sec

α_3 = 88 (for sand)

v = velocity, cm/sec

C_p = coefficient of intrinsic permeability, cm^2

β_3 = 1.2

The usage of this formula requires that the computed velocities at the nodes, which have units of (cm/min) be converted to (ft/sec).

Intrinsic permeabilities are computed from values of the hydraulic conductivity. Since the kinematic viscosity of water is a function of temperature, the value corresponding to the mean annual temperature in the study area was used.

After K_D is computed, it must be converted to units of cm^2/min for usage in the quality calculations. The various conversion factors used in connection with equation (90) are given in the listing of the program (see Appendix G).

SAMPLE CALCULATIONS

In both the flow and quality models, the calculations follow a two-step procedure: 1. compute the values of the coefficients of each node, and 2. solve the resulting system of equations using Gaussian elimination (Hadley, 1964). Step (1) is illustrated below for a single node in the soil profile. Space limitations preclude the illustration of step (2). The soil type considered herein was the sand of the Lake Apopka basin, whose estimated hydraulic characteristics are shown in Figures 42 and 86.

Flow Model

An isolated portion of a soil profile is shown in Figure 79. The calculations to be discussed are those for node j = 5 and time step n = 7. Indicated in the figure are the pressure heads for this node, and its two adjoining nodes, at the previous time step (n = 6). Since the computations of withdrawals (sinks) by plants and artificial drains are explained in Appendix E, these sinks are considered to be zero in this discussion.

The coefficients A_5^7, B_5^7, C_5^7 and D_5^7 can be obtained from the formulas for an interior node, that is, equations (77), (78), (79) and (80). A review of these expressions indicates that to determine certain values of K and C, it is first necessary to compute $\psi_{I_5}^{7}$, $\psi_{II_5}^{7}$ and $\psi_{III_5}^{7}$

Equations (52), (53) and (54) for these three variables contain terms for pressure heads at the present time step, which are yet unknown. Thus these values must be estimated by any one of several methods,

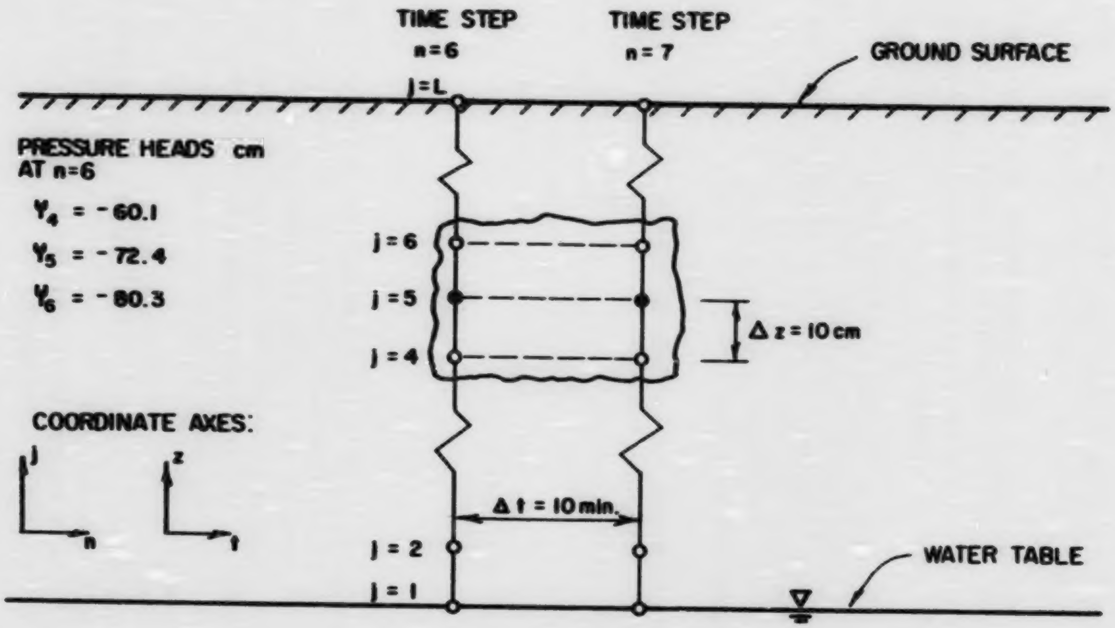

TIME STEP
n=6
TIME STEP
n=7
GROUND SURFACE
j=L
PRESSURE HEADS cm
AT n=6
ψ4 = -60.1
ψ5 = -72.4
ψ6 = -80.3
j=6
j=5
j=4
Δz = 10 cm
COORDINATE AXES:
j
n
z
t
Δt = 10 min.
j = 2
j = 1
WATER TABLE

Figure 79. Illustration of an isolated portion of an unsaturated zone system, showing flow model data.

including regression. For simplicity, these pressure heads are assumed to be equal to those in the previous time step. Substitution into equations (52), (53) and (54) yields:

$$\psi_{I_5}^{7} = \left(\frac{-\ 72.4\ -\ 80.3\ -\ 80.3\ -\ 72.4}{4}\right) = -\ 76.3\ \text{cm}$$

$$\psi_{II_5}^{7} = \left(\frac{-\ 60.1\ -\ 72.4\ -\ 72.4\ -\ 60.1}{4}\right) = -\ 66.2\ \text{cm}$$

$$\psi_{III_5}^{7} = \left(\frac{-\ 72.4\ -\ 72.4}{2}\right) = -\ 72.4\ \text{cm}$$

The conductivities and slope parameters corresponding to these intermediate head values can be estimated from Figures 86 and 42. The resulting coefficients are:

$$A_5^7 = \frac{0.076}{2(10)} = 0.0038$$

$$B_5^7 = \frac{0.076}{2(10)} + \frac{0.096}{2(10)} + \frac{0.00378(10)}{10} = 0.0124$$

$$C_5^7 = \frac{0.096}{2(10)} = 0.0048$$

$$D_5^7 = (0.0038)(-\ 80.3) + \left(\frac{(0.00378)(10)}{(10)} - \frac{0.076}{2(10)} - \frac{0.096}{2(10)}\right)(-\ 72.4)$$

$$+\ (0.0048)(-\ 60.1) + 0.076 - 0.096 + 0 = -\ 0.266$$

Thus, the basic finite-difference equation for $j = 5$ and $n = 7$ is:

$$-\ (0.0048)\psi_4^7 + (0.0124)\psi_5^7 - (0.0038)\psi_6^7 = (-\ 0.266) \qquad (91)$$

Following the computation of pressure heads throughout the soil profile using the elimination technique, it is possible to determine the flow velocity at each node. The finite-difference formula for Darcy's law, applied to node $j = 5$, is:

$$v_5^7 = -K_5^7\left[\frac{(z_4 + \psi_4^7) - (z_6 + \psi_6^7)}{2\Delta z}\right] \tag{92}$$

where v denotes the velocity (cm/min), which is defined as positive in the downward direction, and z the elevation (cm). It may be noted that

$$z_4 - z_6 = 2\Delta z = -20.0 \text{ cm}$$

For demonstration purposes, it may be assumed that $\psi_4^7 = -56.1$, $\psi_5^7 = -69.0$ and $\psi_6^7 = -78.1$. From Figure 86, the conductivity becomes:

$$K_5^7 = 0.074 \text{ cm/min}$$

Substitution into equation (92) produces

$$v_5^7 = -(0.074)\left[\frac{(-56.1) - (-78.1) + (-20)}{2(10)}\right] = 0.0074 \text{ cm/min}$$

Quality Model

The computations of nutrient withdrawals by plants and drains, and of source/sink reaction rates are shown in Appendix E. For this reason, the terms involving these processes are set equal to zero below.

An isolated portion of a soil profile is depicted in Figure 80. Shown therein are assumed values of moisture content, θ, for three nodes at two time steps. Also indicated is the velocity, v, at the middle node at the current time step n = 10, and the concentration at n = 9. In practice, these moisture and velocity values are obtained from the flow model. The concentrations at the various nodes at the current time step constitute the unknowns.

To compute the values of the coefficients AC, BC, CC and DC at node j = 4, it is first necessary to determine the dispersion coefficients at that location. As can be seen in equation (90), the computation of this coefficient requires the values of the kinematic viscosity and hydraulic conductivity.

Values for the kinematic viscosity of water are available for different temperatures (King and Brater, 1963). The subsurface water temperature

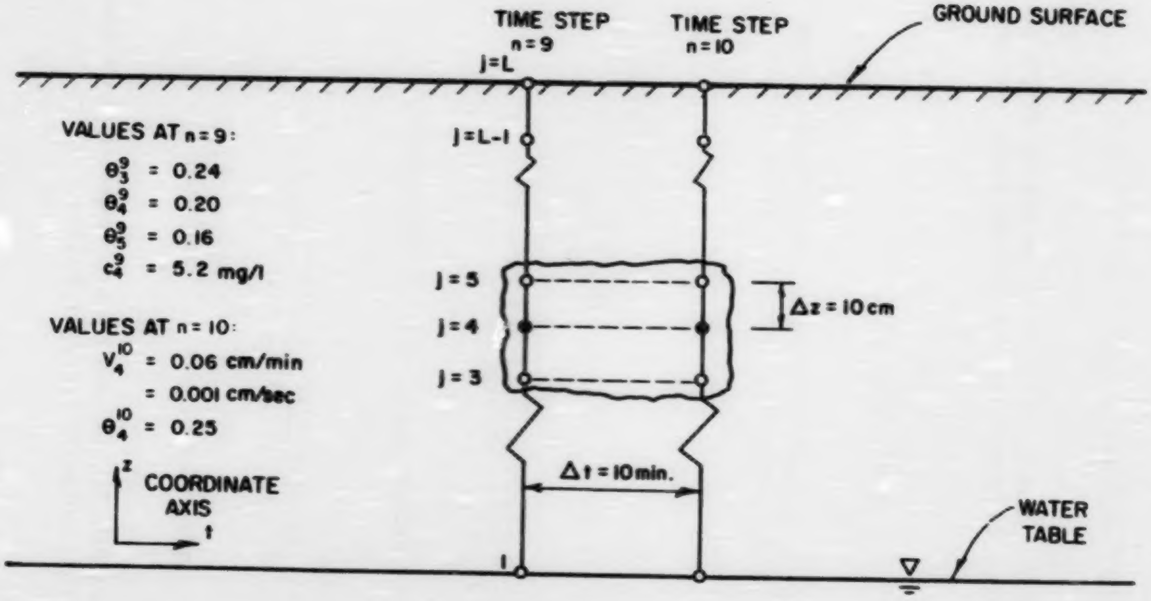

TIME STEP
n=9
TIME STEP
n=10
GROUND SURFACE
j=L
j=L-1
j=5
j=4
j=3
1
Δz = 10 cm
Δt = 10 min.
WATER TABLE
VALUES AT n = 9:
θ_3^9 = 0.24
θ_4^9 = 0.20
θ_5^9 = 0.16
c_4^9 = 5.2 mg/l
VALUES AT n = 10:
V_4^{10} = 0.06 cm/min
= 0.001 cm/sec
θ_4^{10} = 0.25
z
t
COORDINATE AXIS

Figure 80. Illustration of an isolated portion of an unsaturated zone system, showing quality model data.

in the Lake Apopka basin was estimated to be 71.5°F, which is the annual mean value for Orlando, Florida (Lichtler, Anderson and Joyner, 1968). Accordingly,

$$\nu = 1.040 \times 10^{-5}\ \text{ft}^2/\text{sec} = 1.12 \times 10^{-8}\ \text{cm}^2/\text{sec}$$

To determine the hydraulic conductivity, it is necessary first to determine the pressure head corresponding to the moisture content at $j = 4$. From Figure 42,

$$\psi = -\ 59.0\ \text{cm}$$

The corresponding hydraulic conductivity value, K, obtained from Figure 86, is converted to intrinsic permeability by the relationship

$$C_p = K\ \nu/g \tag{93}$$

where g = gravitational acceleration. Thus:

$$C_p = (0.107\ \text{cm/min})\left[1.91(10)^{-7}\frac{\text{cm}^2}{\text{cm/min}}\right] = 2.04 \times 10^{-8}\ \text{cm}^2$$

Substitution of the above values into equation (90) yields

$$K_D = (1.12 \times 10^{-8})(88)\left[\frac{1.0 \times 10^{-3}(2.04 \times 10^{-8})^{0.5}}{1.12 \times 10^{-8}}\right]^{1.2}$$

$$= 1.98 \times 10^{-5}\ \text{cm}^2/\text{sec} = 1.19 \times 10^{-3}\ \text{cm}^2/\text{min}$$

The desired coefficients AC, BC, CC and DC are computed from equations (77), (78), (79) and (80), respectively, as follows:

$$AC_4^{10} = \left[\frac{0.06}{2(10)}\right] + \left[\frac{1.19 \times 10^{-3}}{10^2}\right] = 0.0030119$$

$$BC_4^{10} = \left(\frac{0.25 - 0.20}{10}\right) + \left(\frac{0.25}{10}\right) + \left(\frac{2(1.19 \times 10^{-3})}{10^2}\right) = 0.0750238$$

$$CC_4^{10} = \left(\frac{0.06}{2(10)}\right) + \left(\frac{1.19 \times 10^{-3}}{10^2}\right) = 0.0030119$$

$$DC_4^{10} = 0 + 0 + \left(\frac{(0.25)(5.25)}{10}\right) = 0.13$$

The finite-difference equation for $j = 4$ and $n = 10$ is, therefore

$$-\ (0.0030119)c_3^{10} + (0.0750238)c_4^{10} - (0.0030119)c_5^{10} = (0.13)$$

The system of equations involving all nodes is solved in a manner analogous to that in the flow model.

PROGRAM DESCRIPTION

Quantity Portion

Summary—

The purpose of the model is to solve numerically the one-dimensional, unsteady-state flow equation for an unsaturated porous medium. Initially, the program considers a given vertical column of soil with a certain pressure (moisture content) profile. This column is partitioned into a discrete number of nodes, as shown in Figure 78. At each time step, the program determines the values of hydraulic pressure resulting from the values of two boundary conditions, namely: (1) the combined effect of rainfall and evaporation at the top of the profile, and (2) net recharge rate at the bottom. Since these boundary conditions change with time, it is necessary to conduct an interfacing with the overland flow and groundwater programs.

In addition to the initial tension profile and boundary conditions, some relationships involving moisture, tension pressure and hydraulic conductivity must be provided as inputs to the model. These relationships are essentially fundamental properties of each soil. Therefore, the program computations must be conducted independently for each major soil type. Special formulas are also included to compute withdrawals (sinks) of water at each node in the soil profile.

The output from the unsaturated zone flow model consists basically of the values of moisture content and velocity, obtained from the corresponding pressure heads at the various nodes. One table is printed out for every time step. The velocities affect the movement and dispersion of substances dissolved in the water.

The computer model consists of a main program (designated as MAIN) and several subroutines: COEF, EXTRA, VFLOW, WTABLE, PSIVAL, PSIMID, SINK and MATRIX. Also, four function subprograms are utilized to perform moisture-tension-conductivity conversions. The names of these functions are: CSL, CK, TENS and HUMID. A summary of the main program, subroutines and functions follows.

Main Program—

The main program first reads in the data. A partial list of data is given below:

1. Number of nodes and time steps.
2. Rates of rainfall, evaporation and net recharge flow at each time step.
3. Vertical distance between node and interval between time steps.
4. Initial values of moisture content for all nodes.

Subsequently, some of the values above are converted into consistent units. In the first time step, the moisture values given are used to evaluate the various soil moisture functions.

In the second time step ($N = 2$), the information from the previous step and the boundary conditions are utilized to compute the values of pressure at each node. In carrying out these computations, MAIN calls subroutines PSIMID, COEF, PSIVAL (in that order) and various function subprograms. Thereafter, it calls subroutine VFLOW to determine the vertical velocities at each node in this time step.

For the following time steps ($N > 2$), the calculations are slightly more involved than those for $N = 2$. Subroutines EXTRA and WTABLE are called in addition to those above. Tables of moisture values for each node are printed.

At any time step, the option of plotting the moisture versus depth profile can be exercised. This can be accomplished by calling a special subroutine package.

Subroutine COEF—

At the j-th node in the soil profile, it is possible to write an equation of the form of (55) which relates the pressure head, ψ, at the node in question to the ψ's at its adjoining nodes. The coefficients associated with these three heads are designated in the program as A_j^n, B_j^n and C_j^n, in which the superscript n denotes the time step. The coefficient designated as D_j^n contains all known constants in the equation. In a soil profile containing L nodes, it follows that L equations of the general form described above can be written. The solution of the resulting system of equations (22) requires that L values of the coefficients A_j^n, B_j^n, C_j^n and D_j^n be calculated at every time step. Subroutine COEF performs the calculations for these coefficients.

Two nodes, one lying on the upper boundary and another on the lower boundary of the soil profile, have only one adjacent node instead of the usual two. The calculation of the coefficients associated with these two boundary equations is therefore a special case. It consists of the application of Darcy's law between the boundary node in question and its adjacent node. The flow between the nodes is set equal to the known boundary condition flow.

The values of A_j^n, B_j^n, C_j^n and D_j^n at each node obtained by subroutine COEF are used elsewhere in the program to determine the tension head at every node.

Subroutine EXTRA—

To compute the coefficients mentioned above in subroutine COEF, it is necessary to determine first the value of some moisture properties of the soil, such as hydraulic conductivity, at every node. Unfortunately, these properties are a function of the respective pressure heads, which are not yet known for the time step in question.

For this reason, these pressure heads most be predicted using their computed values from previous time steps. Subroutine EXTRA performs these extrapolations. It may be noted that EXTRA is not called at time step N = 2, since only one set of previous pressure heads is available at that time.

Subroutine PSIMID—

To determine the coefficients A_j^n, B_j^n, C_j^n and D_j^n in subroutine COEF, it is first necessary to evaluate certain soil moisture functions, such as conductivity. The numerical technique requires that some of these functions be evaluated, not at the nodes themselves, but rather at points midway between the nodes. Subroutine PSIMID computes the values of pressure head, ψ, at such midpoint locations, using linear interpolation.

Subroutine SINK—

The option exists in this program to specify certain rates of withdrawal of water (sinks) at each node in the soil profile. These withdrawals can consist of water uptake by plants and/or artificial drainage. In the former category, the uptake rates must be determined from climatic and agricultural information. In the latter case, any one of several semi-empirical formulas to compute drainage rates may be used. Additional information on these two types of calculations is given in Appendix E.

Subroutine SINK adds the plant and drainage withdrawals for each node in the soil column. The resulting values of total sink flows are stored and then utilized in subroutine COEF to calculate the D_j^n coefficients.

Subroutine PSIVAL—

The purpose of subroutine PSIVAL is to assemble the information needed to compute the values of pressure head, ψ, at each node, and then to call subroutine MATRIX to carry out the computations.

First, PSIVAL determines whether the top node is saturated or not. Saturation at this node can be caused by two conditions: (1) net rainfall rate (rainfall minus evaporation) greater than the saturated conductivity of the soil, or (2) existence of a ponding situation due to high previous rainfall. If either one of the above conditions holds, the definition of the boundary condition at the top of the profile is achieved by setting the pressure head at the top node equal to the ponding depth. If these conditions do not hold, the top node is not saturated and the usual upper boundary condition involving Darcy's law applies.

After the proper boundary condition above has been selected, subroutine MATRIX is called to compute the values of pressure head at each node. Subroutine PSIVAL then predicts the depth of ponding (if any) for the next time step.

Subroutine MATRIX—

This subroutine assembles the previously determined values of A_j^n, B_j^n and C_j^n into a left-hand side matrix, and the values of D_j^n into a right-hand side matrix, as shown in system of equations (22). It then proceeds to solve for the unknown values of pressure head, ψ, at each node.

As mentioned previously, the left-hand side matrix is of tri-diagonal form and therefore the system is most easily solvable by an elimination procedure. The specific technique used herein is Gaussian elimination. It may be noted that the occurrence of a ponding condition at the top of the profile introduces some changes in the calculations.

Subroutine WTABLE—

This subroutine determines the elevation of the water table at each time step. To achieve this, it checks the previously computed values of pressure head, starting at the bottom node and proceeding upward. After it locates the first unsaturated node (pressure head less than zero), it computes the water table elevation.

Subroutine VFLOW—
Subroutine VFLOW first utilizes the values of pressure head, determined by subroutine MATRIX, to find the total head (elevation plus pressure) at each node. It then determines the flow of moisture at each node from Darcy's law.

Plotting Subroutines Package—
This package is composed of subroutines GRAPH, PINE, CURVE, PPLOT and function ACOS. The option to plot any tabulated results may be exercised from the main program by calling subroutine GRAPH. This subroutine, in turn, controls the flow of information between the other subroutines in the package.

Function Subprograms—
Four function subprograms are used in this computer model. They all involve basic soil moisture relationships, and their names and purposes are:

1. Function CSL. Computes the slope of the moisture versus pressure head curve, as a function of the latter.
2. Function CK. Finds the hydraulic conductivity for a given value of pressure head.
3. Function TENS. Converts values of moisture content into pressure heads.
4. Function HUMID. Converts pressure heads into moisture contents.

The above relationships may be determined in the field for any given soil type, or may be approximated using literature data for similar soils. The latter approach was used herein. Segmented straight lines were used to fit non-linear relationships.

Quality Portion

Summary—

The main purpose of SOILQUAL is to compute, at every time step, the concentrations of any given substance at the various nodes in a soil profile. The required input data for this program can be broken down into two basic types. The first category consists of water quantity and flow data, obtained by interfacing with the unsaturated flow program. These data include values of flow velocity and moisture content at every node, in addition to initial and boundary conditions. The second type is composed of water quality information, such as fertilizer availability and rate coefficients for source and sink reactions in the soil.

The two types of data discussed above are used by the program to compute the values of coefficients AC_j^n, BC_j^n, CC_j^n, and DC_j^n in equation (75) at every node. Some of these coefficients vanish in the case of the top and bottom nodes, which have only one adjacent node instead of the usual two. The program then proceeds to solve a system of simultaneous equations to obtain the desired concentrations at every node.

The computer model consists of a main program, designated as MAIN, and subroutines GROUP, MAT2 and OUTRIT. Following is a discussion of both the main program and the subroutines.

Main Program—

Initially, MAIN sets up data storage blocks from which to retrieve water quantity information previously obtained by the flow program. Other blocks are designated to store water quality data read into the model, and other water quality parameters generated by the model itself.

After reading in the data, the program performs some simple calculations involving conversion factors, to obtain the desired consistency in units. Next, it utilizes hydraulic results from the flow program to compute the value of the dispersion coefficient at every node.

Subsequently, a loop involving all time steps carries out the following instructions, in order: (1) calls subroutine GROUP to assemble at every node the various terms in equation (74) into an equation of the form of (75), and (2) calls subroutine MAT2 to perform the matrix operations required to solve for the concentrations of substances at each node. At the conclusion of this time loop, MAIN calls subroutine OUTRIT to print out all the pertinent results.

Subroutine GROUP—

At every time step, GROUP determines the values of coefficients AC, BC, CC and DC for every node in the soil system. Recall that the top and bottom nodes constitute special cases. The structure of this subroutine is very similar to that of subroutine COEF in program INFILT.

Subroutine MAT2—

This subroutine inserts the values of AC_j^n, BC_j^n and CC_j^n made available by GROUP into a left-hand side matrix. Also, it inserts the corresponding values of DC_j^n into a right-hand side vector. Subsequently it solves the system of equations in a stepwise fashion using Gaussian elimination. It may be noted that subroutine MAT2 is a modified version of subroutine MATRIX in the unsaturated zone flow model.

Subroutine OUTRIT—

After subroutines GROUP and MAT2 have been called for all the time steps in the period of study, MAIN calls subroutine OUTRIT to print out the results. The most significant information provided by OUTRIT is a table of concentration values at all nodes for all time steps.

APPENDIX C

DETAILS OF GROUNDWATER MODEL

INTRODUCTION

Shown herein are sample calculations for the groundwater flow model as described in Section VI. Space limitations preclude the presentation of counterparts for the quality formulation (Bedient, 1972). Also included are descriptions of the subroutines in both the flow and quality models. Consistent English units are used. Inasmuch as the data are hypothetical, equivalent metric units are not given.

FLOW CALCULATIONS

The basic finite-difference relationship (Freeze, 1966) used in the calculations expresses the hydraulic head at a given node in terms of the heads at its adjoining nodes and other constants:

$$\phi(I,J) = \frac{\begin{array}{l}[K_h(I-1,J)\phi(I-1,J) + K_h(I,J)\phi(I+1,J) \\ \quad + \alpha K_v(I,J-1)\phi(I,J-1) + \alpha K_v(I,J)\phi(I,J+1)]\end{array}}{K_h(I-1,J) + K_h(I,J) + \alpha K_v(I,J-1) + \alpha K_v(I,J)} \tag{94}$$

where ϕ = hydraulic head, ft

K_h, K_v = horizontal and vertical permeabilities, gal per day/ft^2

α = $\left(\frac{\Delta x}{\Delta z}\right)^2$ (dimensionless)

Δx = horizontal spacing, ft

Δz = vertical spacing, ft

Any consistent permeability units could be utilized in this formula, since K_h and K_v act as weighting factors.

To illustrate the usage of equation (94), it is possible to isolate a portion of a grid system, as shown in Figure 81 along with assumed values of the permeabilities and geometric spacings. Also shown are the heads at the various nodes. A new value of head at node (I,J) can be determined by substitution into (94), as follows

$$\phi(I,J) = \frac{\left[(20)(70.0) + (20)(74.0) + \left(\frac{100}{50}\right)^2(40)(69.1) + \left(\frac{100}{50}\right)^2(40)(75.0)\right]}{\left[20 + 20 + \left(\frac{100}{50}\right)^2(40) + \left(\frac{100}{50}\right)^2(40)\right]}$$

$$= 72.2 \text{ ft}$$

Next, a relaxation factor is applied to the computed value to promote convergence in the calculations. The formula used for this purpose is

$$\phi_c(I,J) = w\phi_n(I,J) + (1-w)\phi_p(I,J) \qquad (95)$$

in which w denotes the relaxation factor. The subscripts p, n and c indicate the previous, new and corrected values, respectively. Expression (95) above is the same as equation (39). In this study, the value selected for w was 1.85 (Freeze, 1971). Substitution of the appropriate values into equation (95) yields

$$\phi_c(I,J) = (1.85)(72.2) + (-0.85)(71.1) = 73.2 \text{ ft}$$

Equations (84) and (95) are applied to the various nodes in the groundwater system in an iterative fashion. It may be assumed that after all iterations have been completed, the values of head (ft) at the five nodes in question are:

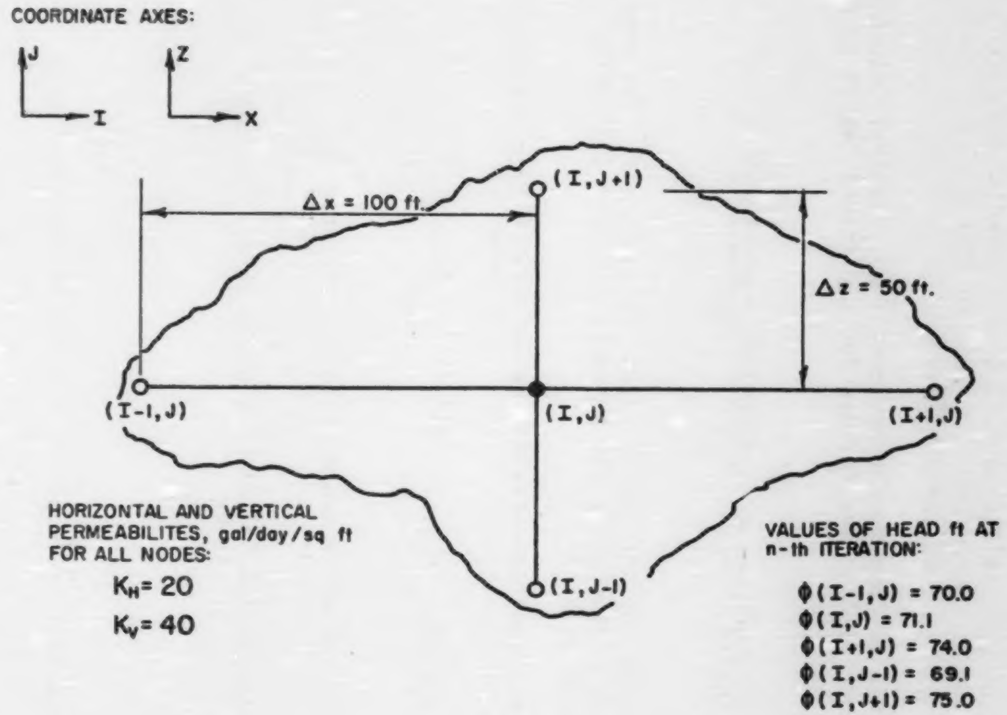

COORDINATE AXES:
J
I
Z
X
Δx = 100 ft.
Δz = 50 ft.
(I,J+1)
(I-1,J)
(I,J)
(I+1,J)
(I,J-1)
HORIZONTAL AND VERTICAL PERMEABILITES, gal/day/sq ft FOR ALL NODES:
K_H = 20
K_V = 40
VALUES OF HEAD ft AT n-th ITERATION:
ϕ(I-1,J) = 70.0
ϕ(I,J) = 71.1
ϕ(I+1,J) = 74.0
ϕ(I,J-1) = 69.1
ϕ(I,J+1) = 75.0

Figure 81. Isolated portion of a groundwater grid system, showing geometry and assumed heads and permeabilities.

$$\phi(I-1,J) = 71.5$$

$$\phi(I,J) = 73.0$$

$$\phi(I+1,J) = 74.4$$

$$\phi(I,J-1) = 71.0$$

$$\phi(I,J+1) = 74.9$$

It is now possible to compute the horizontal and vertical velocity components at node (I,J). The formula for the former, which is based on Darcy's law, is:

$$v_h(I,J) = K_h(I,J)C\left(\frac{\phi(I+1,J) - \phi(I-1,J)}{2\Delta x}\right)$$

where v_h represents the horizontal velocity, in ft/day. The constant C is a factor applied to convert the permeability from $gal/day/ft^2$ to ft/day. Its value is 0.134.

Similarly, the vertical velocity can be calculated from the formula

$$v_v(I,J) = K_v(I,J)C\left(\frac{\phi(I,J+1) - \phi(I,J-1)}{2\Delta z}\right)$$

Substitution into the above two expressions yields

$$v_h = (20)(0.134)\left(\frac{74.4 - 71.5}{2(100)}\right) = 0.039 \text{ ft/day (to the left)}$$

and

$$v_v = (40)(0.134)\left(\frac{74.9 - 71.0}{2(50)}\right) = 0.209 \text{ ft/day (downward)}$$

PROGRAM DESCRIPTION

Quantity Portion

The two-dimensional steady-state groundwater flow model, PHI, consists of a main program (MAIN) and subroutines BOUND, TABLE, EQUIP, VEL and PREDIS. Following is a description of both the main program and its subroutines.

Main Program—
The main program first reads in the data, some of which are listed below:
1. A matrix (NCLASS) for node classification. The numbering system indicates, for instance, whether the node lies on the water table or another boundary, or whether its head value is known. This matrix remains unchanged throughout the program.
2. Horizontal and vertical permeabilities for every node.
3. The values of head at nodes where it is known, and trial values at other nodes.

The program then proceeds to write out the matrix PHI, which contains the information in item (3) above. Next, the iterative procedure to calculate the head at each node where it is unknown is begun. The head at a given node is expressed in terms of the heads and permeabilities of its surrounding nodes, its own permeability and the horizontal and vertical spacings. However, the exact form of the expression varies with the node type as designated in NCLASS. For this reason, several conditional statements in the program check the value of NCLASS for the node under consideration to ascertain the proper formula to be used.

Most nodes are of the interior type, that is, surrounded by four adjacent nodes, and the standard formula for computing head is applicable. Other nodes lie on no-flow boundaries of the grid system and are thus surrounded by fewer than four nodes. In this case, subroutine BOUND is called to perform the head computation. If a certain discontinuity effect occurs at the water table, the head at the affected node is determined by subroutine TABLE. In all the above cases, a relaxation factor is applied to the value of head following its calculation.

After the iterative process to determine the heads throughout the grid system has been completed, MAIN prints out these values in tabular form. It may be noted that any grid nodes located above the water table lie outside the groundwater system. For identification purposes, their head values are printed out as zeros.

Next, subroutine EQUIP is called to determine the location of points of equal head. Subsequently, MAIN calls subroutine VEL to determine the velocities throughout the grid system. The last subroutine called is PREDIS. Its function is to prepare the results obtained for use as input to the water quality program.

Subroutine BOUND—
The subroutine was designed to compute the head at nodes located on a no-flow boundary. The existence of such a boundary can be brought about by an impervious formation or by the flow patterns of a basin. From Darcy's law, it follows that the hydraulic head on both sides of a no-flow boundary must be equal.

Since nodes lying on boundaries are surrounded by fewer than the usual four nodes, BOUND must first establish the location of the missing node(s) (up or down, right or left) with respect to the boundary node in question. Subsequently, it implicitly creates an "image" or imaginary node at that location. To satisfy the no-flow condition, the head at this image node is set equal to that of the node located directly opposite it across the boundary. Finally, the computation for the head at the boundary node in question is carried out.

Subroutine TABLE—
In the unlikely event that a node lying to the right or left of an interior node is located above the water table, the head computation becomes another special case. Subroutine TABLE first establishes which of the adjacent nodes (left, right, or both) lie above the water table. It then branches out to perform the appropriate calculation.

The general condition described above is brought about by large variations in the slope of the water table. By decreasing the spacings in the grid system, the need to utilize subroutine TABLE can be minimized.

Subroutine EQUIP—
This subroutine determines the location in the grid system of points having certain values of head. It uses linear interpolation to achieve this purpose. A table of results is printed.

Subroutine VEL—
Subroutine VEL uses Darcy's law to compute the horizontal and vertical velocity components throughout the grid system. It then uses these components to determine the resultant velocity vector at each node. The direction of this vector is computed as an angle, in degrees, measured counter-clockwise from the positive horizontal axis. Both the magnitude and direction of the velocity vectors are printed out in tabular form.

Subroutine PREDIS—
The function of PREDIS is to assemble the results obtained throughout program PHI for subsequent transfer to the groundwater quality node. The variables used in the interfacing are the velocity components, horizontal and vertical spacings, time step and others. This interfacing can be carried out using punched cards or by means of common storage locations.

Quality Portion

The computer program used herein has basically the same sequence of operations as that developed by Shamir and Harleman (1966), with some modifications introduced by Bedient (1972). Since the latter has provided a detailed description of the program, only a brief summary is given below.

The computer model consists of a main program (MAIN) and the following subroutines: CINPUT, TRIX, TRIY, EXPLIC, COEFX, COEFY, CFEXP, VCALC and OUTPUT. The function of MAIN is to read in preliminary data, compute the dispersion coefficients, and control the sequence of operations performed by the various subroutines.

Subroutine CINPUT reads in concentration data used as initial and boundary conditions. The purpose of COEFX and COEFY is to provide the values of the coefficients and right-hand side constants for all equations of the type of (40) and (41), respectively. The two systems of equations corresponding to these types are solved by TRIX and TRIY.

After the computations involving the alternating direction implicit procedure have been completed, subroutine EXPLIC obtains the final concentration values using an explicit scheme. The coefficients used in this matrix solution are provided by CFEXP.

If desirable, it is possible to read in velocity values from a tape by calling VCALC. This subroutine also performs some necessary averaging calculations. Finally, subroutine OUTPUT prints out a table of pollutant concentrations at each grid node, at any given time step.

APPENDIX D

DETAILS ON INTERFACING METHODOLOGY

A generalized schematic representation of the overlay procedure used in this study is provided in Figure 82 which shows the basic branching system containing the main program and various model subroutines. Each of these model subroutines corresponds to a major partition in the hydrologic system and, in turn, contains other subroutines of lesser hierarchy.

In the present formulation, any given subroutine can only be called once during a simulation run. For instance, subroutines SUB1A and SUB2A might in effect be identical, but their names cannot be the same. The capability of re-using a subroutine name at different times in the simulation would have required additional job control language (JCL) statements and input/output instructions. These complexities were thought to be unwarranted from a demonstration standpoint. Also, the current relative inefficiency of the computations can be reduced by the use of object decks, preferably within a program library.

Example JCL instructions for the overlay procedure applicable on the IBM 370/165 at the University of Florida are given in Figure 83. The overlay requires that the program setup be carried out through the linkage editor, instead of the less sophisticated loader. Source or object programs may be used, but their locations in the deck differ. The different data sets are defined toward the end of the deck. In the University of Florida system, data sets 5, 6 and 7 are reserved for reading, writing and punching cards, respectively.

Lists of interfacing variables between the different types of model subroutines are provided in Figure 84. The pertinent information for the Stormwater Management Runoff and Receiving Models is available elsewhere (Environmental Protection Agency, 1971).

A listing of the main program used for an overlay run may be found toward the beginning of Appendix G. Defined therein are the names of model subroutines and data sets used for the various subsystems of the Lake Apopka basin. Also included is the calling sequence for the model subroutines.

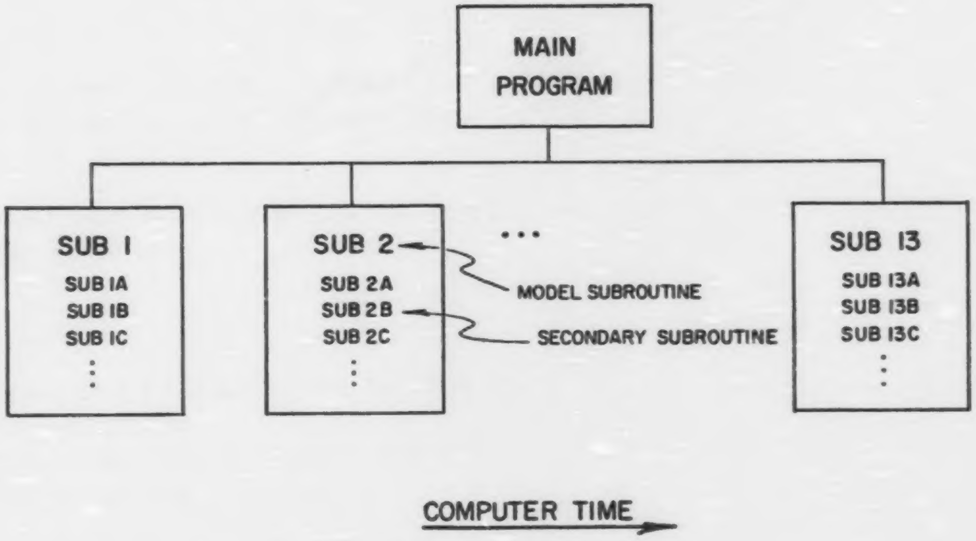

MAIN PROGRAM
SUB 1
SUB 1A
SUB 1B
SUB 1C
SUB 2
SUB 2A
SUB 2B
SUB 2C
MODEL SUBROUTINE
SECONDARY SUBROUTINE
SUB 13
SUB 13A
SUB 13B
SUB 13C
COMPUTER TIME

Figure 82. Generalized hierarchial representation of overlay procedure.

```
// EXEC  F4GCLM , PARM.LKED = 'LIST, MAP, ØVLY'
// FØRT. SYSIN DD *

 (Insert Source Programs)

/*
// LKED. SYSIN DD *

(Insert Object Programs)          Arbitrary Name

        OVERLAY ALPHA
        INSERT SUB1, SUB1A, SUB1B, SUB1C, ...
        OVERLAY ALPHA
        INSERT SUB 2, SUB 2A, SUB 2B, SUB 2C,...
             .
             .
             .
        OVERLAY ALPHA
        INSERT  SUB 13, SUB 13A, SUB 13B, SUB13C, ...
/*                 Data Set Number
GO.FT01F001  DD UNIT = SYSDA, SPACE = (CYL , (2,1))
GO.FT02F001 DD UNIT = SYSDA, SPACE = (CYL , (2,1))
             .
             .
             .
//GO. SYSIN  DD*
```

Figure 83. Job control language (JCL) instructions for overlay procedure valid on IBM 370/65 computer at the University of Florida.

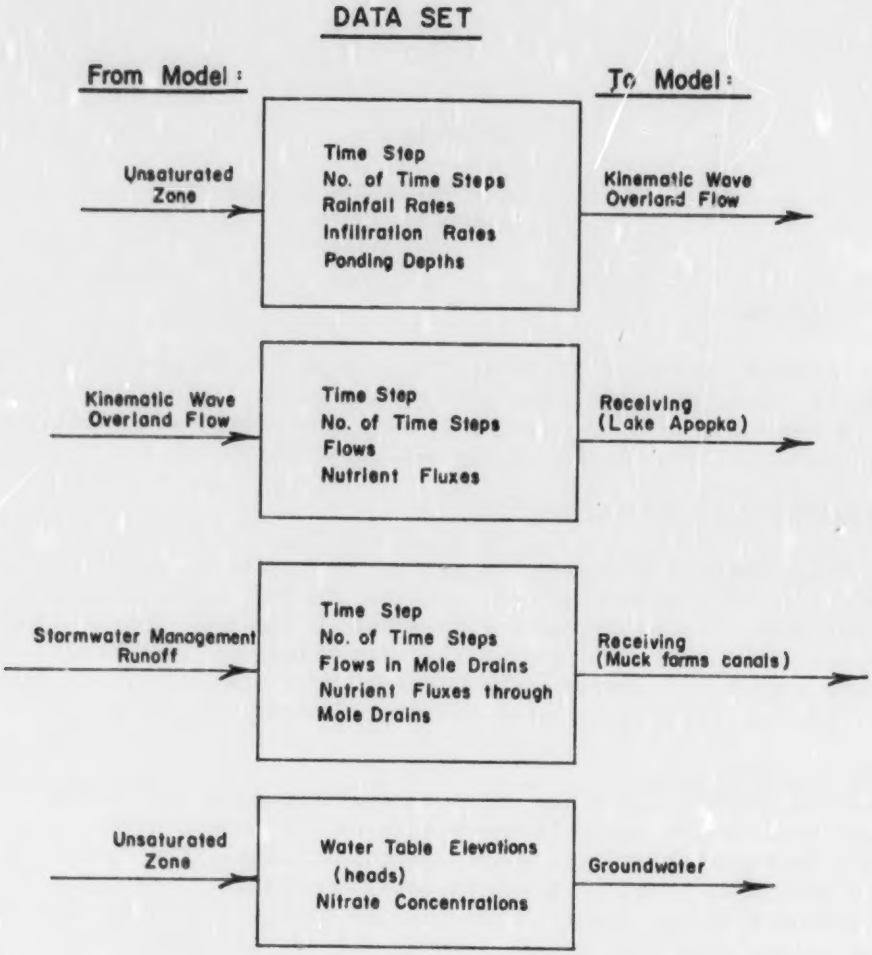

DATA SET
From Model:
To Model:
Unsaturated Zone
Time Step
No. of Time Steps
Rainfall Rates
Infiltration Rates
Ponding Depths
Kinematic Wave Overland Flow
Kinematic Wave Overland Flow
Time Step
No. of Time Steps
Flows
Nutrient Fluxes
Receiving (Lake Apopka)
Stormwater Management Runoff
Time Step
No. of Time Steps
Flows in Mole Drains
Nutrient Fluxes through Mole Drains
Receiving (Muck farms canals)
Unsaturated Zone
Water Table Elevations (heads)
Nitrate Concentrations
Groundwater

Figure 84. List of major interfacing variables for the various models.

APPENDIX E

DETAILS ON APPLICATION TO THE LAKE APOPKA BASIN

INTRODUCTION

This appendix contains brief discussions on hydrologic and nutrient budgets conducted within the Lake Apopka basin. These are followed by explanations of various agricultural calculations. Finally, several lists of data used in this study are provided.

HYDROLOGIC AND NUTRIENT BUDGETS

Budgeting efforts have been attempted for two portions of the study area: (1) Lake Apopka and (2) the muck farms. Calculations for the former were carried out as a supplement to the more detailed modeling computations which constituted the main thrust of this study. The latter budget was conducted by Heaney, Perez and Fox (1972) for the East Central Florida Regional Planning Council.

Lake Apopka Budget

Numerous sources and sinks of water and associated nutrients were considered in the analysis. For some of the budget items, such as Gourd Neck Spring and the Apopka-Beauclair Canal, the available data were adequate. Most of the data deficiencies involved items related to the muck farms, namely: (1) pumpage rates, (2) flows through the flap values, and (3) seepage through the earthen dike.

The approach taken in the hydrologic budget was to lump the three items above into an unaccounted-for inflow term. Monthly estimates of other sources and sinks, along with lake stage data, were used to solve for the unaccounted-for inflow. The results obtained for years 1961 through 1970 indicated the existence of significant average annual flows from the muck farms to the lake. However, in some months the computed flows occurred from the lake to the farms.

Measured nitrogen and phosphorous concentrations at the various sources and sinks were utilized in the estimation of a nutrient budget for the lake. Due to lack of data, nutrient cycling between the lake sediments and the water was not considered in the calculations. Also, the hydrologic indeterminacy involving the three items at the lake-muck farm interface posed severe difficulties in computing a net nutrient flux. At best, only limiting values could be estimated. In any case, the various budget results indicated a significant overall net influx of nutrients into Lake Apopka.

Space limitations preclude the presentation of the specific assumptions and results of both the hydrologic and nutrient budgets. However, this information has been tabulated and filed for possible subsequent use. An examination of the hydrologic budget developed by Anderson (1971) should also be useful.

Muck Farms Budget

The hydrologic indeterminacy mentioned above, among other data deficiencies, precluded an accurate estimate of both the hydrologic and nutrient budgets within the muck farms. Since the overall results may be found in a report by Heaney, Perez and Fox (1972), it is more pertinent to discuss certain items which provided insight into modeling approaches.

One of these items consisted of the nutrient contribution by rainfall. It was determined that this source is significantly smaller than fertilizer application. Therefore, rainfall was not considered in defining the upper boundary conditions in the quality portion of the unsaturated zone model. This omission was also made in the sandy soils area.

Computed yearly average fertilizer application rates were used to estimate nutrient concentrations at the uppermost node of the soil profile. Estimated harvest weights and nutrient contents of the various vegetable crops in the muck farms were utilized to determine nutrient withdrawal (sink) rates from the soil.

Finally, consideration was given to the release of nutrients by the muck soil. If the soil losses in the muck farms were comparable to those in the Florida Everglades of 1 in/yr (2.5 cm/yr) (Stephens, 1969), the corresponding nutrient losses could be very significant.

CALCULATIONS

Agricultural calculations conducted in the Lake Apopka basin involved both types of overland flow models and the unsaturated zone formulation.

Overland Flow

The usage of the duBoys formula (Einstein, 1964) to compute sediment loads at the catchment outlets was illustrated in Appendix A. It is also of interest to consider the routing of phosphorous and nitrogen in overland flow.

Certain soils (e.g., muck) contain large amounts of nutrients, predominantly in organic form. Thus, these nutrients are transported as part of suspended solids loads. Due to the short duration of overland flow phenomena, it was considered unlikely that significant amounts of nutrients would be released by the soil particles. However, it is expected that significant releases could occur in the receiving bodies of water.

Since organic N and P fluxes can be estimated from soil chemical data and predicted suspended soilds loads, separate attention was given to the inorganic forms of these nutrients.

Phosphorous Routing–

The only inorganic phosphorous source considered herein was fertilizer application. Data on fertilizer loading rates for the study area were coupled with generalizations on phosphorous behavior in soils (Stanford, England and Taylor, 1970).

Agricultural phosphorous is fixed rapidly to most soils, and thus travels with suspended particles in overland flow. For this reason, the weight fraction of this substance in the soil was sought.

The calculations may be illustrated by referring to Figure 85. Part (a) of this figure constitutes a top view of an arbitrary square plot within the sandy soils region. The area of this plot is one acre. Part (b) is a lateral cross-section of the plot. Illustrated is the estimated phosphorous loading rate corresponding to fertilizer application in citrus groves of 60 lb/ac/yr (64.4 kg/ha/yr), obtained from the East Central Florida Regional Planning Council. Since the citrus groves occupy approximately one-half of the total area of sandy soils, the areal average application rate was assumed to be 30 lb P/ac/yr (32.2 kg/ha/yr).

Several simplifying assumptions were necessary to estimate the distribution of the applied P within the soil profile. One was that 90 percent of the applied amount remained within the top six inches of the profile. It was also assumed that the distribution was uniform with depth within this range (see Figure 85).

Following application, phosphorous is slowly removed from the soil by plants. The remaining amount at any time depends, therefore, on the

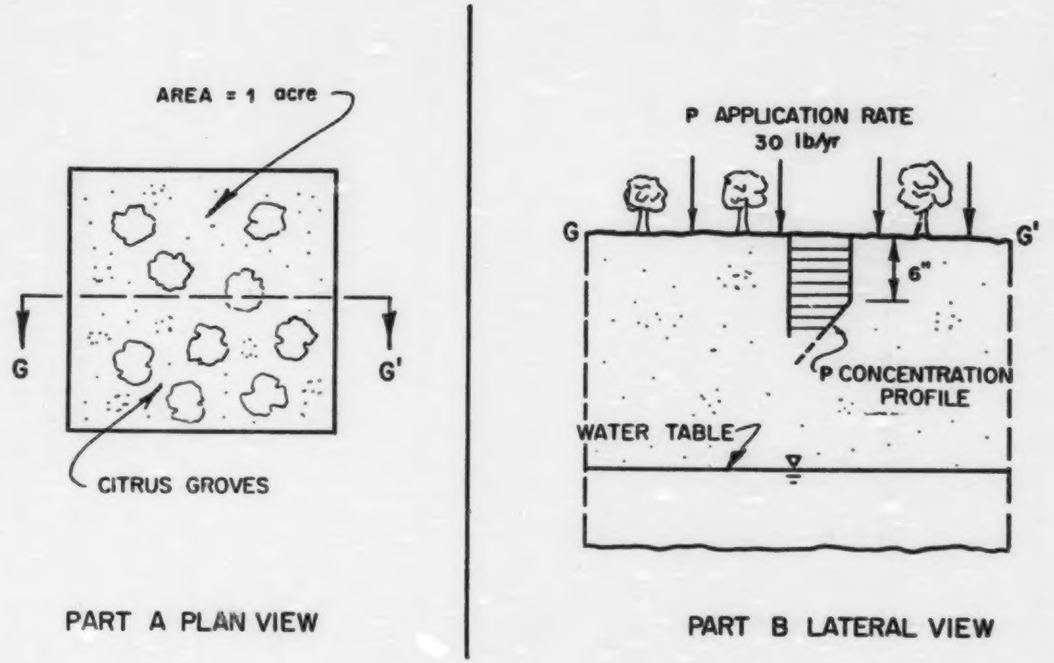

AREA = 1 acre
G
G'
CITRUS GROVES
PART A PLAN VIEW
P APPLICATION RATE
30 lb/yr
G
G'
6"
P CONCENTRATION PROFILE
WATER TABLE
PART B LATERAL VIEW

Figure 85. Illustration of fertilizer application on a plot in the sandy soils.

time elapsed since application and the growth characteristics of the crop. A gross assumption was made that, on a time-average basis, the P remaining in the soil was one-half of the applied amount.

The concentration of P within the top six inches (15 cm) can be computed as:

$$c_P = \frac{(0.90)\left(\frac{1}{2}\right)(30 \text{ lb})}{(6 \text{ in})\left(\frac{1}{12}\frac{\text{ft}}{\text{in}}\right)(1 \text{ ac})\left(43{,}560 \frac{\text{ft}^2}{\text{ac}}\right)}$$

$$= 6.18 \times 10^{-4} \frac{\text{lb P}}{\text{ft}^3} = 9.93 \times 10^{-3} \frac{\text{Kg P}}{\text{m}^3}$$

About 43 percent of the sandy soil is occupied by voids. Thus, the concentration in the soil itself becomes

$$c_P' = \frac{100}{(100-43)} c_P = 1.08 \times 10^{-3} \frac{\text{lb P}}{\text{ft}^3 \text{ sand}} = 1.73 \times 10^{-2} \frac{\text{Kg P}}{\text{m}^3 \text{ sand}}$$

That is, suspended solids fluxes must be multiplied by c_P' to obtain the phosphorous fluxes.

The calculations for the muck soils were based on similar assumptions. The value of c_P' obtained was 4.25×10^{-3}(lb P/ft^3 muck); or metric — 6.92×10^{-2}(Kg P/m^3 muck).

Nitrogen Routing—
According to Stanford, England and Taylor (1970), nitrogen applied in fertilizers is generally readily converted to nitrate ion. This substance leaches rapidly through soils.

In this study, the contribution of agricultural nitrogen to overland flow was viewed to occur, not as part of an erosion process, but rather as diffusion upward from the soil water. It was thought that the rate of transfer might decrease exponentially with time, and such a relationship was incorporated into the model. However, due to lack of data these transfers were tentatively assumed to be zero.

Unsaturated Zone

Calculations for the unsaturated zone involved consideration of diverse items, ranging from soil curves to source/sink effects within the soil.

Hydraulic Conductivity Curves—

Plots of assumed pressure versus conductivity relationships for sandy and muck soils are provided in Figure 86 and 87, respectively. Only the saturated conductivities for these two soils could be estimated with reasonable accuracy (Stewart, Powell and Hammond, 1963; Harrison and Weaver, 1958). No data were available for unsaturated conditions. In the muck, this deficiency is less likely to be severe because the soil is maintained close to field capacity. The curve for sandy soil was set by visual comparison to curves reported by Freeze (1969).

Mole Drains—

The expression used to compute the flows through the mole drains in the muck farms was the following (Harrison, 1960):

$$Q = \frac{4Kh\left(2d_e + h\right)}{S} \qquad (96)$$

where Q = discharge, m^3/hr per unit length in m

K = hydraulic conductivity, m/hr

h = vertical distance between water table and drain, m

d_e = thickness of an "equivalent layer", m

S = spacing, m

The discharge on a per unit area basis, q, can be obtained by dividing the above expression by the spacing, as illustrated in Figure 88, part (a):

$$q = \frac{Q}{S} \qquad (97)$$

Accordingly, the units of q are $m^3/hr/m^2$, or m/hr. For consistency with equation (50) in Appendix B, the units of q are converted to cm/min:

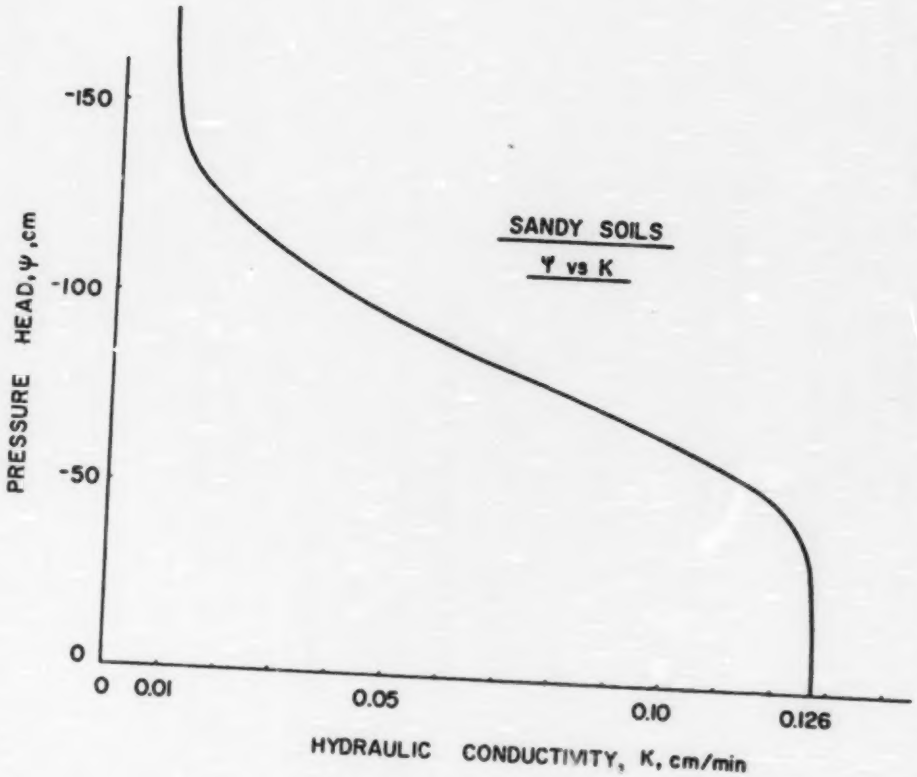


Figure 86. Assumed pressure versus hydraulic conductivity relationship for sandy soils.

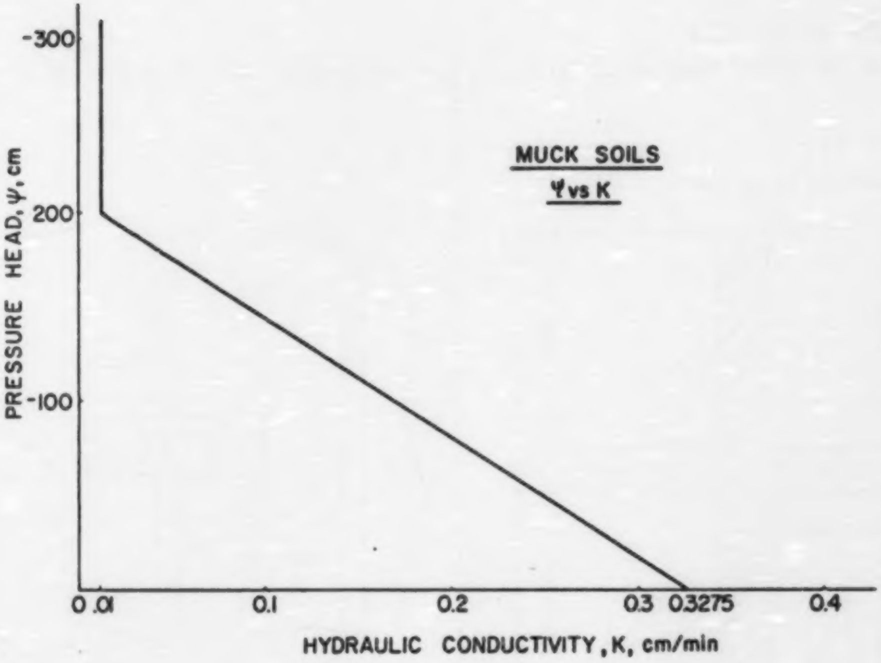
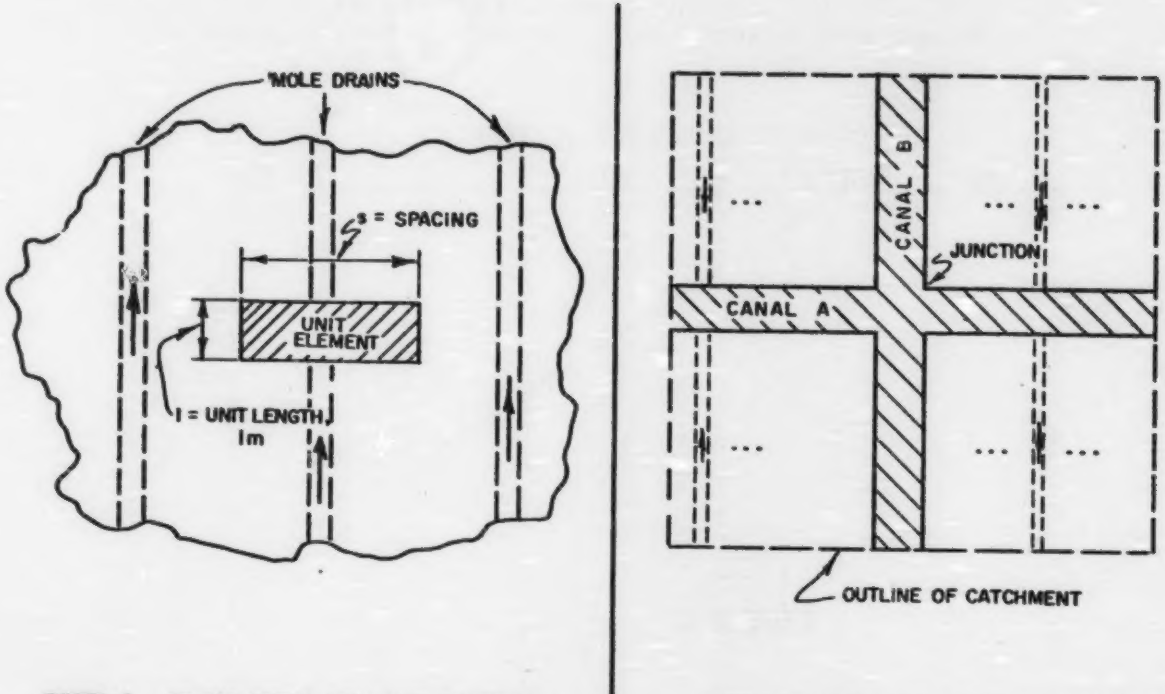


Figure 87. Assumed pressure versus hydraulic conductivity relationship for muck soils.


MOLE DRAINS
s = SPACING
UNIT ELEMENT
l = UNIT LENGTH, 1m
CANAL B
JUNCTION
CANAL A
OUTLINE OF CATCHMENT

PART A PLAN VIEW OF UNIT ELEMENT

PART B TOP VIEW OF THE MOLE DRAINS AND CANAL SYSTEMS

Figure 88. Illustration of layout of mole drains.

$$q' = q\frac{100\ \frac{cm}{m}}{60\ \frac{min}{hr}}$$

Finally, the discharge must be expressed on a per unit depth basis:

$$q_d = \frac{q'}{\Delta z} \tag{98}$$

in which Δz represents the vertical spacing (cm). The variable q_d (1/min) represents the sink term for mole drains.

To compute the contribution of the mole drains to a given junction in the receiving model, it is necessary to determine the total length of drains feeding into such a junction. An approximate relation for this length, L, is:

$$L = \frac{A}{S} \tag{99}$$

in which A represents the area of the runoff catchment and S denotes the spacing. The total flow then becomes

$$Q_T = QL \tag{100}$$

where Q is the flow per unit length computed from equation (96). Appropriate unit conversions must be carried out in equation (100).

The nutrient fluxes into the receiving junctions were computed using the flows from equation (100) and concentration data collected by Hortenstine and Forbes (1971).

Top Boundary Condition—
The concentration value at the top node, resulting from fertilizer loads, depends upon the time elapsed since application, uptake by plants and other conditions in the soil. For simplicity, the computation of this value is illustrated for the situation immediately following application.

The loading rate for phosphorous in the sandy soils was estimated at 30 lb/ac/yr (32.2 Kg/ha/yr). It is assumed that following application, the entire amount becomes uniformly distributed with depth, down to a distance $\Delta z/2$ from the ground surface. The vertical spacing, previously selected, was 17 cm. For convenience, a saturation condition may be assumed to exist at the top node. Accordingly, the volumetric moisture fraction is 0.43.

The concentration in the soil water, c, can be computed as follows:

$$c = \frac{\text{weight}}{\text{volume}} = \frac{30 \text{ lb} \times 454 \frac{\text{g}}{\text{lb}} \times 10^3 \frac{\text{mg}}{\text{g}}}{0.43 \times 1 \text{ ac} \times 43{,}560 \frac{\text{ft}^2}{\text{ac}} \times 8.5 \text{ cm} \times \frac{1}{30} \frac{\text{ft}}{\text{cm}} \times 28.32 \frac{\text{l}}{\text{ft}^3}}$$

$$= 9.2 \frac{\text{mg P}}{\text{l}}$$

Analogous calculations may be conducted for nitrogen.

Plant Withdrawals—

Quantity— Data on evapo-transpiration rates for a given area provide the starting point for calculations involving water uptake by plants. For instance, for the citrus groves in the Lake Apopka basin it was estimated that four-fifths of the total water loss from the soil constituted transpiration by the crops. Data on total evapo-transpiration rates for citrus groves in Florida have been compiled by Hashemi and Gerber (1967).

It is known that water uptake by crops is not uniform throughout the root zone but, rather, decreases with depth. Several distributions of this uptake were considered in preliminary calculations. However, it was found that overall model results for short simulation periods were insensitive to plant withdrawals, which are significant only on a long-term basis. For this reason, it was decided to assume a uniform withdrawal pattern and thus simplify programming instructions.

To illustrate the computation of the sink terms, it may be assumed that the total uptake by citrus is 0.10 in/day (0.25 cm/day). Assuming also a root zone depth of five feet (1.5 m) and the designation of 10 nodes within that zone (see Figure 89) the withdrawal rate at a given node is:

$$W = \frac{0.10 \text{ in/day}}{10 \text{ nodes}} = 10^{-2} \text{ in/day} = 1.76 \times 10^{-5} \text{ cm/min}$$

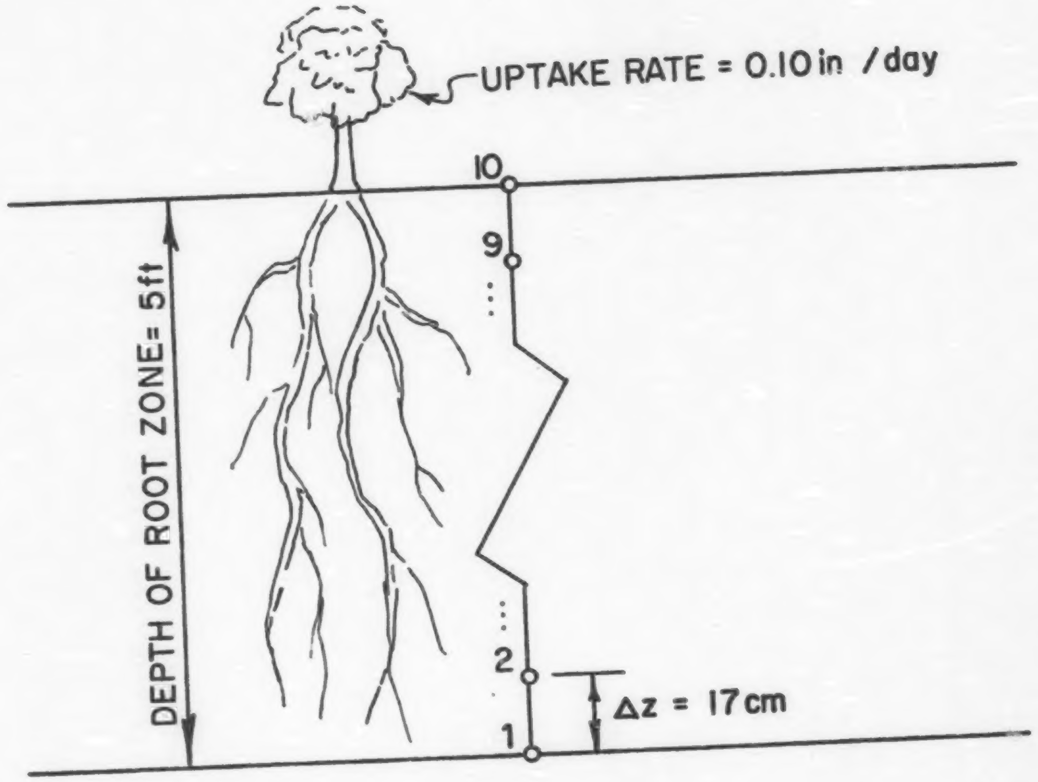

UPTAKE RATE = 0.10 in /day
10
9
⋮
⋮
2
1
DEPTH OF ROOT ZONE= 5ft
Δz = 17cm

Figure 89. Illustration of water uptake by citrus.

This value must be converted to a per unit depth basis:

$$w = \frac{W}{\Delta z} = \frac{1.76 \times 10^{-5}\ \frac{\text{cm}}{\text{min}}}{5\ \text{ft} \times 30.4\ \frac{\text{cm}}{\text{ft}} \times \frac{1}{(10-1)}} = 1.03 \times 10^{-6}\ \frac{1}{\text{min}}$$

The units of w are consistent with those specified for a sink in equation (50).

In the computer program, the soil tension at each node is checked prior to computing the sink term. If the tension exceeds that for the wilting point, a withdrawal of zero is specified. It is perhaps likely that, in practice, a no-withdrawal condition might result from even smaller tensions.

Quality— The nutrient withdrawal pattern within the soil profile should follow that of water uptake, since nutrients are dissolved in water. However, for simplicity, nutrient uptake was assumed to be uniform with depth. Also, seasonal effects and crop growth patterns were not considered.

In the muck farms, the nutrient uptake rates were estimated from the N and P contents of the crops and their harvest weights. Yearly withdrawals were 96.0 lb/ac (103 Kg/ha) for N and 8.9 lb/ac (9.6 Kg/ha) for P (Heaney, Perez and Fox, 1972).

Calculation of the nitrogen sink term may be illustrated by converting the withdrawal rate into equivalent units of nitrate

$$96.0\ \text{lb N} = 96.0 \times \frac{62}{14} = 427\ \text{lb}\ NO_3^- = 194\ \text{Kg}\ NO_3^-$$

Assuming a root depth of one foot (0.3 m), and a node spacing of 6.7 cm, the uptake for a given node becomes, on a per month basis:

$$u = \left(427\ \frac{\text{lb}}{\text{ac-yr}} \times \frac{1}{12}\ \frac{\text{yr}}{\text{mo}}\right) \times \frac{6.7\ \text{cm}}{1\ \text{ft} \times 30.5\ \frac{\text{cm}}{\text{ft}}}, \text{ or}$$

$$u = 7.8\ \frac{\text{lb}\ NO_3^-}{\text{ac-mo}} = 8.4\ \frac{\text{Kg}\ NO_3^-}{\text{ha-mo}}$$

For consistency within equation (73), the desired units for this withdrawal rate are (mg/ l/min):

$$u = \frac{\left(7.8\ \frac{\text{lb}}{\text{mo}}\right)\left(10.35\ \frac{\frac{\text{mg}}{\text{min}}}{\frac{\text{lb}}{\text{mo}}}\right)}{(1\ \text{ac})(6.7\ \text{cm})\left(4.05 \times 10^{4}\ \frac{1}{\text{ac-cm}}\right)\theta} = \frac{2.97 \times 10^{-4}}{\theta}\ \frac{\text{mg/l}}{\text{min}}$$

in which θ is the volumetric moisture fraction. Assuming $\theta = 0.75$, the uptake becomes

$$u = 3.97 \times 10^{-4}\ \text{mg}\ NO_3^-/\text{l/min}$$

The calculations for phosphorous follow the same steps.

Little information was available on nutrient uptake by the citrus in the Lake Apopka basin. One approach used to estimate this uptake was to examine the ratios of plant nutrient withdrawals to fertilizer loading rates in the muck farms and attempt a correlation. Data on this aspect of citrus would be desirable.

Soil Source/Sink Effects–
Since these soils are unlikely to release nutrients, the soil medium should act as a net sink for both nitrate and phosphorous, especially the latter. However, due to lack of data, these sink terms were tentatively set at zero.

On the other hand, muck soils are known to release nutrients. Little quantitative information is available on the release mechanism, but for illustrative purposes it may be tied to the consolidation of these soils (Stephens, 1969).

The nutrient release resulting from a hypothetical one inch (2.54 cm) yearly soil loss can be estimated from data on nutrient contents of muck (Forbes, 1971). Since these data are expressed on a percent dry weight basis, it is necessary to estimate the weight of one inch of soil over an area of, say, one acre (0.4 ha): Assuming that the dry muck unit weight is 100 lb/ft^3 (1606 Kg/m^3) the weight can be computed as:

$$W = 1\ \mathrm{in} \times \frac{1}{12}\frac{\mathrm{ft}}{\mathrm{in}} \times 4.356 \times 10^4\ \frac{\mathrm{ft}^2}{\mathrm{ac}} \times 1\ \mathrm{ac} \times 100\ \frac{\mathrm{lb}}{\mathrm{ft}^3} = 3.63 \times 10^5\ \mathrm{lb}$$

$$= 1.65 \times 10^5\ \mathrm{Kg}$$

The nitrogen content of muck is 2.79 percent. Thus, the amount of this substance released is:

$$r = \frac{2.79}{100} \times 3.63 \times 10^5 = 10.1 \times 10^3\ \frac{\mathrm{lb\ N}}{\mathrm{ac}} = 10.9 \times 10^3\ \frac{\mathrm{Kg\ N}}{\mathrm{ha}}$$

Assuming that this loss occurs over a period of one year and that all the nitrogen is converted to the nitrate form

$$r = 10.1 \times 10^3 \times \frac{62}{14} = 4.48 \times 10^4\ \frac{\mathrm{lb}\ \overline{\mathrm{NO_3}}}{\mathrm{ac\text{-}yr}} = 4.82 \times 10^4\ \frac{\mathrm{Kg}\ \overline{\mathrm{NO_3}}}{\mathrm{ha\text{-}yr}}$$

The units for this release rate are the same as the original units used for the harvest removal estimates in the muck farms. Therefore, conversion into the desired sink units of mg/l/min is carried out in the same manner as in the plant nutrient withdrawal calculations. Hopefully, a better understanding of release mechanisms should suggest improvements in the corresponding calculations.

LIST OF DATA

The scope of this investigation precluded a separate sampling program. Nevertheless, substantial amounts of available data collected by various agencies were assembled. These data are summarized in Tables 1 through 4. Indicated are the sampling frequency, agency and other pertinent information.

Most of these data have been punched on computer cards. The original tabulations, which are mostly in computer coding sheets, are also on file.

TABLE 1

List of Hydrologic Data for Lake Apopka Basin

Item	Location	Source	Dates	Sampling Frequency	Comments
Pumping rates from muck farms to Lake Apopka	Zellwood and Duda muck farms	East Central Florida Regional Planning Council (ECFRPC)	1967-1970	Daily, with gaps	Not broken down by individual pumps
Rainfall	Clermont and Lisbon stations near Lake Apopka	ESSA (Weather Bureau)	1936-1970	Monthly and daily	Monthly 1936-1970 Daily 1967-1970
Stage-area data, before and after muck farms	Lake Apopka	USGS			Areas available on 0.1 ft. stage intervals
Pan evaporation	Lisbon station near Lake Apopka	ESSA (Weather Bureau)	1961-1970	Monthly	
Pan evaporation	Lisbon station	ESSA (Weather Bureau)	1967-1970	Daily	
Lake stage data	Lake Apopka	USGS	1936-1970	Daily	
Rainfall data	Stations in muck farms	Muck farms	1961-1970	Daily, with gaps	
Apopka-Beauclair Canal flows	North shore of Lake Apopka	USGS	1967-1970	Daily	
Piezometric levels	Orange County and Lake County	USGS	1968-1971	Twice per year	

TABLE 1—*Continued*

Item	Location	Source	Dates	Sampling Frequency	Comments
Coordinates of wells	Orange County and Lake County	USGS			Longitude and latitude
Rainfall data	Apopka-Beauclair Canal	ECFRPC		Monthly	
Apopka-Beauclair Canal flows	North shore of Lake Apopka	USGS	1936-1967	Monthly, with numerous gaps	

TABLE 2

List of Agricultural Data for Lake Apopka Basin

Item	Location	Source	Dates	Sampling Frequency	Comments
Land use data	Lake Apopka basin	Soil Conservation Service (SCS)	Recent		
Acres planted with a given crop	Muck farms	East Central Florida Regional Planning Council	1970-1971	Weekly	
Fertilizer types for various crops	Muck farms	ECFRPC	1970-1971		
Portions of farms lying in each runoff subcatchment	Muck farms	ECFRPC	1970-1971		
Amounts of fertilizer applied to various crops	Muck farms	ECFRPC	1970-1971		
Areas of runoff subcatchment	Muck farms	ECFRPC	1970-1971		
Farm areas	Muck farms	ECFRPC	1970-1971		

TABLE 3

Water Quality Data for the Lake Apopka Basin

Item	Location	Source	Dates	Sampling Frequency	Comments
Water quality parameters, including N and P	21 stations in Lake Apopka	Orange County Pollution Control Dept. (OCPCD)	1967-1970	Once every month or 2 months	
Water quality parameters, as above	Shallow wells around Lake Apopka	OCPCD	1970	Monthly	
Water quality parameters, as above	Stations in muck farms canals	OCPCD	1968-1970	Monthly	
Water quality parameters, as above	3 stations in Winter Garden Canal	OCPCD	1969-1970	Every 2 weeks	
Typical values of various water quality parameters	10 stations in Lake Apopka	Florida State Board of Health (FSBH)	October 1962 and January 1963		
Various water quality parameters	21 sampling stations in Lake Apopka	FSBH	First half of 1964	Every 2 weeks	
Ions and solids	21 bottom sampling stations in Lake Apopka	OCPCD	Summer 1967	Once	
Sediment core samples including	Stations as shown in	EPA (Schneider	Report dated 1968	Approximately 3 times each station	

TABLE 3—*Continued*

Item	Location	Source	Dates	Sampling Frequency	Comments
nutrients and solids	report	and Little) Appendix B			
Nutrient concentrations	Rainwater, shallow wells and artesian wells in Lake Apopka basin	EPA (Schneider and Little) Appendix C	Report dated 1968	Once	
Effect of lake bottom on fish feed organisms	Lake Apopka	FSBH report dated 1964	1947-1963	Every 2 years	Qualitative comments for each station
Biological organisms (mainly bottom)	Lake Apopka	OCPCD	1967-1970	Every 3 months	
Phosphorous data	Muck farms and Lake Apopka	Dr. Forbes (IFAS, Univ. of Florida)	1967-1970	Monthly	
Chemical and biological parameters	Lake Johns (south of Lake Apopka)	OCPCD	1966-1969	Every 3 months	
Nutrient concentrations	Percolating water in muck farms	Drs. Forbes and Hortenstine (IFAS, Univ. of Florida)	1971	Seasonal	Being prepared for publication

APPENDIX F

SUMMARY OF ADDITIONAL REFERENCES ON AGRICULTURAL NUTRIENTS

Although the state of the art in hydrologic modeling is at a relatively advanced stage, much remains to be accomplished in the modeling of agricultural water quality. Hopefully, the references mentioned herein should be of some value in formulating needed improvements.

One source of nutrients not considered in this study was animal wastes, due to their insignificance in the Lake Apopka basin. However, this source can often be important, as pointed out by Townshend, Reichert and Nodwell (1969). These researchers provided figures on nutrient contributions by different animals, expressed in terms of human population equivalents. They also discussed trends in animal populations in Ontario, Canada. Webber and Lane (1969) studied the different nitrogen compounds contained in manure and the ensuing reactions in the soil.

Water quality characteristics of runoff from cattle feedlots were investigated by Norton and Hansen (1969). Their study comprised both a mathematical development of overland flow and a quality sampling program. Their results should provide useful insights into water quality modeling approaches.

Other investigations on overland flow quality include those by Gilchrist and Gillingham (1970) and by Nelson and Romkens (1970). These two papers deal primarily with field studies on phosphorous movement resulting from different fertilizer application rates, and could be used as guides for sampling programs in a given area. Data on the concentration of different ions in overland flow have been collected by Gburek and Heald (1970). Bacterial levels in runoff have been reported by Kunkle (1970).

The calculation of an inventory of nutrient sources and sinks in a given area can be facilitated by the use of the tabular approach proposed by Schultz (1970). This was the basic approach used for the budgeting calculations in the muck farms of the Lake Apopka basin. Insight into the economics of fertilizer application is provided in a paper by Fox and Allee (1970).

APPENDIX G

LISTING OF COMPUTER PROGRAMS

Included herein are listings for the following models: (1) unsaturated zone, (2) kinematic wave overland flow and (3) groundwater. Listings for the stormwater management runoff and receiving programs are available elsewhere (Environmental Protection Agency. 1971).

A listing of the executive program, used in connection with the overlay technique, is provided first. Usage of this program is optional.

```
C     MAIN PROGRAM FOR INTERFACING
C     COMMON BLOCKS ONE, UNSAT1 AND NUM1 RE-NAMED ID TO SAVE CORE SPACE
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      NGWIF=1
      NUNIF1=2
      NUNOV1=3
      NUNRE1=4
      NUNGW1=8
      NUNRE2=9
      NUNIF2=10
      NUNOV2=11
      NUNOV3=12
      NUNOV4=13
      NUNIF3=14
      NUNGW2=15
      NUNGW3=16
      NOVRE1=17
      NOVRE2=18
      NRERE1=19
      NRERE2=20
      NOVRE3=21
C------------------------------------------------------
C                     UNSATURATED ZONE MODELS
      CALL UNZON1
C     SANDY SOILS AROUND SOUTHERN HALF OF LAKE
      CALL UNZON2
C     MUCK SOILS (ZELLWOOD AND DUDA) ON NORTHERN SHORE OF LAKE
      CALL UNZON3
C     SANDY SOILS NORTH OF MUCK FARMS
C     ----------------------
C                     OVERLAND FLOW MODELS
      CALL OVLAN1
C     SANDY SOILS AROUND SOUTHERN HALF OF LAKE
      CALL OVLAN2
C     SANDY SOILS NORTH OF MUCK FARMS
      CALL OVLAN3
C     ZELLWOOD DISTRICT IN MUCK FARMS
      CALL OVLAN4
C     DUDA DISTRICT IN MUCK FARMS
C     ----------------------
C                     RECEIVING WATER MODELS
      CALL REC1
C     CANALS IN ZELLWOOD DISTRICT
      CALL REC2
C     CANALS IN DUDA DISTRICT
      CALL REC3
C     LAKE APOPKA
C     ----------------------
C                     GROUNDWATER MODELS
      CALL GWBLOK
C     S.W. TO N.E. CROSS-SECTION
C------------------------------------------------------
C                     LIST OF DATA SETS
C     NUMBER          NAME      FROM      TO
C     1               NGWIF     GWBLOK    GWBLOK
C     2               NUNIF1    UNZON1    UNZON1
C     3               NUNOV1    UNZON1    OVLAN1
C     4               NUNRE1    UNZON2    REC1
C     5               (READ)
C     6               (WRITE)
C     7               (PUNCH)
C     8               NUNGW1    UNZON1    GWBLOK
C     9               NUNRE2    UNZON2    REC2
C     10              NUNIF2    UNZON2    UNZON2
C     11              NUNOV2    UNZON2    OVLAN3
C     12              NUNOV3    UNZON2    OVLAN4
```

```
C      13            NUNOV4     UNZON3     OVLAN2
C      14            NUNIF3     UNZON3     UNZON3
C      15            NUNGW2     UNZON2     GWBLOK
C      16            NUNGW3     UNZON3     GWBLOK
C      17            NOVRE1     OVLAN3     REC1
C      18            NOVRE2     OVLAN4     REC2
C      19            NRERE1     REC1       REC3
C      20            NRERE2     REC2       REC3
C      21            NOVRE3     OVLAN1     REC3
C      -------------------------------------------
       END
       SUBROUTINE UNZON1
       COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
       RETURN
       END
       SUBROUTINE UNZON2
       COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
       RETURN
       END
       SUBROUTINE UNZON3
       COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
       CALL UNFLO
       CALL SOILQU
       CALL TRAN
       RETURN
       END
       SUBROUTINE UNFLO
C      UNSATURATED FLOW (INFILTRATION) PROGRAM                          INFL   1
C      ONE-DIMENSIONAL (VERTICAL) UNSTEADY STATE                        INFL   2
C      AT EACH TIME STEP, THE PROGRAM USES BOUNDARY CONDITIONS AND      INFL   3
C        INFORMATION FROM THE PREVIOUS TIME STEPS TO COMPUTE THE TENSION INFL  4
C          HEAD, (PSI), AT EACH NODE IN THE VERTICAL PROFILE.           INFL   5
C      THEREAFTER, THE PROGRAM COMPUTES AND STORES MOISTURE FLUXES      INFL   6
C        BETWEEN NODES. HYSTERESIS EFFECTS ARE NOT CONSIDERED           INFL   7
C-------------------------------------------------
C                LIST OF VARIABLES
C      NNODES=NO OF NODES IN PROFILE
C      NSTEPS=NO OF TIME STEPS
C      TSTART=STARTING TIME OF SIMULATION, IN MIN.
C      TEND=ENDING TIME OF SIMULATION, IN MIN
C      RAIN=RAINFALL RATE
C      EVAP=EVAPORATION RATE
C      GWFLOW=NET RECHARGE AT BOTTOM BOUNDARY
C      DELZ=VERTICAL SPACING, IN CM.
C      DELT=TIME STEP, IN MIN.
C      THENOT=INITIAL MOISTURE CONTENT
C      ZDRAIN=ELEVATION OF ARTIFICIAL DRAIN
C      ZBOTOM=ELEVATION OF BOTTOM NODE
C      PSINOT=INITIAL PRESSURE HEAD VALUE
C      PSI=PRESSURE HEAD
C      CSLOPE=SLOPE OF MOISTURE VS TENSION CURVE
C      COND=HYDRAULIC CONDUCTIVITY
C      NODSAT=NO OF UPPERMOST NODE THAT IS SATURATED
C      A= A-COEFFICIENT IN TRIDIAGONAL MATRIX USED TO FIND PSI VALUES
C      B= B-COEFFICIENT IN TRIDIAGONAL MATRIX USED TO FIND PSI VALUES
C      C= C-COEFFICIENT IN TRIDIAGONAL MATRIX USED TO FIND PSI VALUES
C      D= D-COEFFICIENT FOR RIGHT HAND SIDE OF MATRIX SCHEME USED TO FIND
C         PSI VALUES
C      P1,P2,P3,=SYMBOLS FOR PSI AT MIDPOINT LOCATIONS (SEE FREEZE,1969)
C      C1,C2=CONDUCTIVITIES CORRESPONDING TO P1,P2
C      R=EXCESS RAINFALL (RAINFALL MINUS EVAPORATION)
C      DELPSI=DIFFERENCE IN PSI VALUES
```

```
C     ZABV,ZBEL=ELEVATION AT UPPER AND LOWER NODES, RESPECTIVELY
C     PHIABV,PHIBEL=PRESSURE HEADS AT UPPER AND LOWER NODES,RESPECTIVELY
C     GRAD12=PRESSURE HEAD GRADIENT BETWEEN NODES 1 AND 2
C     ZTABLE=ELEVATION OF WATER TABLE
C     NNSAT=INDEX COUNTING NUMBER FOR NUMBER OF SATURATED NODES,
C        STARTING AT BOTTOM
C     HPOND=PONDING DEPTH AT GROUND SURFACE
C     PSIGND=PRESSURE HEAD VALUE AT TOP NODE
C     SATCON=SATURATED CONDUCTIVITY
C     QPLANT=FLOW UPTAKE BY PLANTS AT A NODE
C     QDRAIN=FLOW WITHDRAWAL BY DRAIN AT A NODE
C     QSINK=TOTAL SINK(WITHDRAWAL) AT A NODE
C     XL=ARRAY FOR COEFFICIENTS A,B AND C (SEE ABOVE)
C     RHS=RIGHT-HAND SIDE VECTOR FOR D-COEFFICIENTS (SEE ABOVE)
C     TENS=TENSION PRESSURE
C     CK=CONDUCTIVITY
C     CSL=SLOPE OF MOISTURE VS PRESSURE HEAD CURVE
C     HUMID = MOISTURE CONTENT
C     ETCROP=WATER WITHDRAWAL(E-T) BY CROPS IN STUDY AREA
C     WILTM=WILTING POINT MOISTURE OF A GIVEN SOIL
C     RINF=INFILTRATION RATE (DOWNWARD VELOCITY BETWEEN TWO TOP
C     NODES) IN CENTIMETERS/MIN
C     DROOT=DEPTH OF ROOT ZONE (FT)
C     QMOLD=FLOW OUT OF A MOLE DRAIN (CFS/FT)
C     JTAB=NODE AT WHICH WATER TABLE IS LOCATED
C     HTAB=HEIGHT OF WATER TABLE ABOVE BOTTOM OF UNSATURATED PROFILE,
C             IN FEET.
C-----------------------------------------------------
      COMMON/IO /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),INFL   9
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),   INFL  10
     3 PSI2(50,20),PSI3(50,20),                          NODSAT(20),    INFL  11
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),        INFL  12
     5 QPLANT(50,20)                                                    INFL  13
      COMMON/LAB/ TITLE(20),XLAB(11),YLAB(6),HORIZ(20),VERT(6)          INFL  14
      DIMENSION G(650)                                                  INFL  15
      DIMENSION TIT(20)                                                 INFL  16
      COMMON/CROP/ETCROP,WILTM
      COMMON/ROOT/DROOT
      COMMON/MOLE/QMOLD(50)
      COMMON/INF/RINF(50)
      COMMON/RFALL/QRAIN(50)
      COMMON/POND/QPOND(50)
      COMMON/TIME/NTIME,DTIME
      COMMON/SOIL/KSOIL
      COMMON/LOCMOL/LMOLE
      COMMON/WTAB/JTAB(50),HTAB(50)
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      READ (5,100) NNODES,NSTEPS                                        INFL  17
      WRITE (6,101) NNODES                                              INFL  18
  101 FORMAT (' NO OF NODES=',I5)                                       INFL  19
  100 FORMAT (2I3)                                                      INFL  20
      NTIME=NSTEPS
      READ (5,120) TSTART,TEND                                          INFL  21
  120 FORMAT (2F8.2)                                                    INFL  22
C     RAINFALL IN INCHES/HOUR                                           INFL  25
      READ (5,140) (RAIN(I),I=1,NSTEPS)                                 INFL  26
  140 FORMAT (15F5.2)                                                   INFL  27
C     EVAPORATION IN INCHES/HOUR                                        INFL  28
      READ (5,150) (EVAP(I),I=1,NSTEPS)                                 INFL  29
  150 FORMAT (15F5.2)                                                   INFL  30
      WRITE (6,141)                                                     INFL  31
  141 FORMAT ('1',20X,'RAINFALL AND EVAPORATION IN INCHES/HOUR')        INFL  32
      WRITE (6,142)                                                     INFL  33
  142 FORMAT (' TIME STEP',5X,'RAINFALL',7X,'EVAPORATION')              INFL  34
      DO 143 I=1,NSTEPS                                                 INFL  35
      WRITE (6,144) I,RAIN(I),EVAP(I)                                   INFL  36
  144 FORMAT (I10,5X,F10.3,7X,F10.3)                                    INFL  37
  143 CONTINUE                                                          INFL  38
C     GROUNDWATER FLOW IN FT/DAY                                        INFL  39
      READ (5,160) (GWFLOW(I),I=1,NSTEPS)                               INFL  40
  160 FORMAT (15F5.2)                                                   INFL  41
      WRITE (6,162)
  162 FORMAT (20X,'GROUNDWATER FLOW IN FT/DAY')
      DO 163 I=1,NSTEPS
      WRITE (6,164)  I,GWFLOW(I)
  164 FORMAT ( ' TIME STEP',I5,'RECHARGE',F5.2)
  163 CONTINUE
      READ (5,195) DELZ,DELT                                            INFL  42
  195 FORMAT (2F6.2)                                                    INFL  43
      WRITE (6,161) DELZ,DELT                                           INFL  44
  161 FORMAT (' SPACING IN CM IS',F8.3 ,5X,'TIME STEP IN MIN IS',F8.3)  INFL  45
C     READ PRESSURE HEADS RATHER THAN MOISTURE CONTENTS
C     READ (5,190) (THENOT(J),J=1,NNODES)                               INFL  46
C 190 FORMAT (10F6.2)                                                   INFL  47
      DTIME=DELT
      READ (5,130) (PSINOT(J),J=1,NNODES)
  130 FORMAT (10F6.2)
C     READ (5,170) (ZTABLE(I),I=1,NSTEPS)                               INFL  50
C 170 FORMAT (10F6.2)                                                   INFL  51
C     FOR SANDY SOILS IN STUDY AREA VALUES BELOW ARE ARBITRARY
C     SINCE TERRAIN IS UNDULATING.  ALSO, NO DRAINS EXIST
C     IN THESE PARTICULAR SANDY SOILS.
      READ (5,180) ZDRAIN,ZBOTOM,NOD                                    INFL  52
  180 FORMAT (2F6.2,I5)                                                 INFL  53
      LHOLE=NOD
      READ (5,205)  (HORIZ(I),I=1,20)                                   INFL  54
      READ (5,205) (VERT(I),I=1,6)                                      INFL  55
  205 FORMAT (20A4)                                                     INFL  56
      READ (5,210) (TIT  (I),I=1,20)                                    INFL  57
  210 FORMAT (20A4)                                                     INFL  58
C     READ IN WITHDRAWAL RATE FOR CROPS IN SANDY SOILS (HERE,CITRUS)
C     IN INCHES/DAY.  FROM HASHEMI AND GERBER (1967).
      READ (5,7500) ETCROP,WILTM,DROOT
 7500 FORMAT (F5.3,2F5.2)
      READ(5,7600) KSOIL
 7600 FORMAT (I2)
C     SOIL CLASSES AS FOLLOWS--1.SW SAND,2. MUCK, 3.NE SAND
C-----------------------------------------------------------------------INFL  59
C     CONVERT RAW DATA ON RAINFALL,EVAPORATION,AND GROUNDWATER FLOW     INFL  60
C       INTO PROPER AND CONSISTENT UNITS.                               INFL  61
      DO 200 I=1,NSTEPS                                                 INFL  62
C     CONVERT INCHES/HOUR TO CM/MIN, BELOW                              INFL  63
      RAIN(I) = RAIN(I)*0.0423333                                       INFL  64
      RRAIN(I)=RAIN(I)
      EVAP(I) = EVAP(I)*0.0423333                                       INFL  65
C     CONVERT FT/DAY TO CM/MIN,BELOW                                    INFL  66
      GWFLOW(I) = GWFLOW(I)*0.02116666                                  INFL  67
  200 CONTINUE                                                          INFL  68
C     CONVERT CROP WITHDRAWAL FROM IN/DAY TO CM/MIN
      ETCROP=ETCROP*0.00176
C     CONVERT WILTING POINT MOISTURE FROM PERCENT TO FRACTION
      WILTM=WILTM/100.
C     FOR THE 1ST TIME STEP, COMPUTE VALUES OF VARIABLES                INFL  69
C       WHICH DEPEND ON PSI                                             INFL  70
C     -----------------------------------------
      N = 1                                                             INFL  71
      NODSAT(N) = 1                                                     INFL  72
      DO 300 J=1,NNODES                                                 INFL  73
      PSI(N,J) = PSINOT(J)                                              INFL  76
      X = PSINOT(J)                                                     INFL  77
      CSLOPE(N,J) = CSL(X)                                              INFL  78
      COND(N,J) = CK(X)                                                 INFL  79
  300 CONTINUE                                                          INFL  80
```

```
      L = NNODES
      CALL VFLOW(N,L,DELZ,ZBOTOM)
C     LOCATE WATER TABLE
      CALL WTABLE(N,L,DELZ,ZBOTOM)
      WRITE (6,3000)
      WRITE (6,3500) N
      DO 2100 J=1,L
      WRITE (6,2500) J,PSI(N,J)
 2100 CONTINUE
      DO6300J=1,L
      X=PSI(N,J)
      THETA(N,J)=HUMIC(X)
 6300 CONTINUE
C     WRITE OUT MOISTURE VALUES
      WRITE(6,5000)
      WRITE(6,5500) N
      DO6200J=1,L
      WRITE(6,6500) J,THETA(N,J)
 6200 CONTINUE
C     PREPARE INFORMATION FOR PLOTTING ROUTINE
      KKK=1
      NPLOT=L
      NSTEP2=L
      NCURVE=1
      K=1
      DO 3800 J=1,L
      G(K)=J
      G(K+1)=THETA(N,J)
      K=K+2
 3800 CONTINUE
      CALL GRAPH (NPLOT,KKK,NSTEP2,NCURVE,G,TIT)
C     PROCEED TO 2ND TIME STEP.
C     ASSUME COND(1+1/2,,J+(-)1/2) = COND(1,J+(-)1/2) AND
C     SIMILARLY WITH CSLOPE. (RUBIN AND STEINHARDT, 1963).
C     THUS, FORMULAS FOR PSI(I),PSI(II),PSI(III) ARE SPECIAL
C     CASES OF THOSE USED FOR N 2.
C     ---------------------------------------------
      N = 2
      NODSAT(N) = 1
C     FIND VALUES OF PSI(I),PSI(II),PSI(III)
      CALL PSIMID(N,L)
C     FIND COEFFICIENTS A,B,C,D
      CALL COEF(N,L,DELZ,ZBOTOM,NOD,DELT)
C     FIND VALUES OF PSI
      CALL PSIVAL(N,L,DELT,DELZ)
C     FIND VERTICAL VELOCITIES
      CALL VFLOW(N,L,DELZ,ZBOTOM)
C     LOCATE WATER TABLE
      CALL WTABLE(N,L,DELZ,ZBOTOM)
      WRITE (6,3000)
      WRITE (6,3500) N
      DO 2200 J=1,L
      WRITE (6,2500) J,PSI(N,J)
 2200 CONTINUE
      DO6400J=1,L
      X=PSI(N,J)
      THETA(N,J)=HUMIC(X)
 6400 CONTINUE
C     WRITE OUT MOISTURE VALUES
      WRITE(6,5000)
      WRITE(6,5500) N
      DO6600J=1,L
      WRITE(6,6500) J,THETA(N,J)
 6600 CONTINUE
C     PREPARE INFORMATION FOR PLOTTING ROUTINE
      KKK=1
      NPLOT=L
      NSTEP2=L
      NCURVE=1                                                          INFL134
      K=1                                                               INFL135
      DO 3900 J=1,L                                                     INFL136
      G(K)=J                                                            INFL137
      G(K+1)=THETA(N,J)                                                 INFL138
      K=K+2                                                             INFL139
 3900 CONTINUE                                                          INFL140
      CALL GRAPH (NPLOT,KKK,NSTEP2,NCURVE,G,TIT)                        INFL141
C     PROCEED ITERATIVELY FOR REMAINING TIME STEPS                      INFL142
C     ----------------------------------------
      DO 1000 N=3,NSTEPS,1                                              INFL143
      IF(N.EQ.3) NODSAT(N) = 1                                          INFL144
C     PREDICT PSI VALUES AT THIS TIME STEP                              INFL145
      CALL EXTRA(N,L)                                                   INFL146
C     FIND VALUES OF PSI(I),PSI(II),PSI(III)                            INFL147
      CALL PSIMID(N,L)                                                  INFL148
C     FIND COEFFICIENTS A,B,C,D                                         INFL149
      CALL COEF(N,L,DELZ,ZBOTOM,NOD,DELT)                               INFL150
C     FIND VALUES OF PSI                                                INFL151
      CALL PSIVAL(N,L,DELT,DELZ)                                        INFL152
C     FIND VERTICAL VELOCITIES                                          INFL153
      CALL VFLOW(N,L,DELZ,ZBOTOM)                                       INFL154
C     LOCATE WATER TABLE NODE FOR NEXT TIME STEP                        INFL155
      CALL WTABLE(N,L,DELZ,ZBOTOM)                                      INFL156
C-------------------------------------------------------                INFL157
C     WRITE OUT PSI VALUES FOR ALL TIME STEPS                           INFL158
      WRITE (6,3000)                                                    INFL159
 3000 FORMAT ('1',20X,'TABLE OF PRESSURE HEADS IN CM')
      WRITE (6,3500) N                                                  INFL161
 3500 FORMAT (5X,'TIME STEP=',I5)                                       INFL162
      DO 2000 J=1,L                                                     INFL163
      WRITE (6,2500)  J,PSI(N,J)                                        INFL164
 2500 FORMAT (I5,E8.2)                                                  INFL165
 2000 CONTINUE                                                          INFL166
      DO4500J=1,L                                                       INFL167
      X=PSI(N,J)                                                        INFL168
      THETA(N,J)=HUMIC(X)                                               INFL169
 4500 CONTINUE                                                          INFL170
C     WRITE OUT MOISTURE VALUES (PER CENT BY VOLUME).                   INFL171
      WRITE(6,5000)                                                     INFL172
 5000 FORMAT('1',20X,'TABLE OF MOISTURE VALUES AS PER CENT BY VOLUME')  INFL173
      WRITE (6,5500) N                                                  INFL174
 5500 FORMAT (5X,'TIME STEP=',I5)                                       INFL175
      DO6000J=1,L                                                       INFL176
      WRITE (6,6500) J,THETA(N,J)                                       INFL177
 6500 FORMAT (I5,F6.1)                                                  INFL178
 6000 CONTINUE                                                          INFL179
C     PREPARE INFORMATION FOR PLOTTING ROUTINE                          INFL180
      KKK=1                                                             INFL181
      NPLOT=L                                                           INFL182
      NSTEP2=L                                                          INFL183
      NCURVE=1                                                          INFL184
      K=1                                                               INFL185
      DO 3700 J=1,L                                                     INFL186
      G(K)=J                                                            INFL187
      G(K+1)=THETA(N,J)                                                 INFL188
      K=K+2                                                             INFL189
 3700 CONTINUE                                                          INFL190
      CALL GRAPH (NPLOT,KKK,NSTEP2,NCURVE,G,TIT)                        INFL191
 1000 CONTINUE                                                          INFL192
C--------------------------------------
C     WRITE DATA FOR QUALITY PORTION
      WRITE (NUNIF3)DELZ,DELT,NSTEPS,NNODES,DROOT
      DO 4700 N=1,NSTEPS
      WRITE (NUNIF3)(COND(N,J),J=1,NNODES)
 4700 CONTINUE
      DO 4800 N=1,NSTEPS
      WRITE (NUNIF3)(VELZ(N,J),J=1,NNODES)
 4800 CONTINUE
      DO 4900 N=1,NSTEPS
      WRITE (NUNIF3)(THETA(N,J),J=1,NNODES)
 4900 CONTINUE
      WRITE (NUNIF3)(QMOLD(N),N=1,NSTEPS)
      END FILE NUNIF3
      REWIND NUNIF3
      RETURN
      END                                                               INFL196
      SUBROUTINE COEF(N,L,DELZ,ZBOTOM,NOD,DELT)                         INFL197
C     COMPUTES VALUES OF COEFFICIENTS A,B,C,D                           INFL198
      COMMON/ID /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),INFL200
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),   INFL201
     3 PSI2(50,20),PSI3(50,20),                   NODSAT(20),           INFL202
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),        INFL203
     5 QPLANT(50,20)                                                    INFL204
      CALL SINK(N,L,NOD,DELT,DELZ)
C     DEFINE A,B,C,D AT J=1 (BOTTOM)                                    INFL206
      J=1                                                               INFL207
      PSI12=(PSI(N,J)+PSI(N,J+1))/2.                                    INFL208
      COND12=CK(PSI12)                                                  INFL209
      Z1=ZBOTOM*100./3.28                                               INFL210
      Z2=Z1 +DELZ                                                       INFL211
      A(N,J)=1.                                                         INFL212
      B(N,J)=1.                                                         INFL213
      C(N,J)=0.                                                         INFL214
C     GROUNDWATER FLOW IS POSITIVE DOWNWARD                             INFL215
      D(N,J)=Z2-Z1-(-GWFLOW(N)*DELZ/COND12)                             INFL216
     1 - (-(QSINK(N,J)*(DELZ/2.)*DELZ)/COND12)
      LL = L-1                                                          INFL217
      DO 300 J=2,LL                                                     INFL218
      P1 = PSI1(N,J)                                                    INFL219
      P2 = PSI2(N,J)                                                    INFL220
      P3 = PSI3(N,J)                                                    INFL221
      CK1 = CK(P1)                                                      INFL222
      CK2 = CK(P2)                                                      INFL223
      A(N,J) = CK1/(2*DELZ)                                             INFL224
      C(N,J) = CK2/(2*DELZ)                                             INFL225
      B1 = A(N,J)                                                       INFL226
      B2 = C(N,J)                                                       INFL227
      B3 = CSL(P3)*DELZ/DELT                                            INFL228
      B(N,J) = B1+B2+B3                                                 INFL229
C     VALUES OF QSINK ARE INPUTS TU D BELOW                             INFL230
      D(N,J) = A(N,J)*PSI(N-1,J+1) + (B3-B1-B2)*PSI(N-1,J)              INFL231
     1 + C(N,J)*PSI(N-1,J-1) + CK1 - CK2 - (QSINK(N,J)*DELZ)            INFL232
  300 CONTINUE                                                          INFL233
C     DEFINE A,B,C,D AT GROUND SURFACE                                  INFL234
      J=L                                                               INFL235
      A(N,L)=0.                                                         INFL236
      B(N,L)=1.                                                         INFL237
      C(N,L)=1.                                                         INFL238
      X=PSI2(N,L)                                                       INFL239
      R=RAIN(N)-EVAP(N)                                                 INFL240
      ZL1=ZBOTOM*100./3.28+(L-2)*DELZ                                   INFL241
      ZL=ZL1+DELZ                                                       INFL242
C     NET RAINFALL IS POSITIVE DOWNWARD                                 INFL243
      D(N,L)=(R*DELZ/CK(X))-ZL+ZL1 - (QSINK(N,J)*(DELZ/2.)*DELZ/CK(X))
      RETURN                                                            INFL245
      END                                                               INFL246
      SUBROUTINE EXTRA (N,L)                                            EXTR   1
C     USING EXTRAPOLATION FORMULAS, PREDICTS VALUES OF                  EXTR   2
C       PSI FOR THIS TIME STEP.                                         EXTR   3
      COMMON/ID /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),EXTR   5
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),   EXTR   6
     3 PSI2(50,20),PSI3(50,20),                   NODSAT(20),           EXTR   7
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),        EXTR   8
     5 CPLANT(50,20)
       DO500J=1,L                                                      EXTR   9
C      DELPSI = PSI(N-1,J) - PSI(N-2,J)                                EXTR  12
C      PSI(N,J) = PSI(N-1,J) + DELPSI                                  EXTR  13
C      INSTEAD OF EXTRAPOLATING AS ABOVE, USE VALUES FROM PREVIOUS     EXTR  14
C      TIME STEP TO EVALUATE THE VARIOUS SOIL FUNCTIONS
       PSI(N,J)=PSI(N-1,J)
   500 CONTINUE
       RETURN                                                          EXTR  15
       END                                                             EXTR  16
       SUBROUTINE VFLOW(N,L,DELZ,ZBOTOM)                               EXTR  17
       COMMON/ID /PSINCT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),  VFLO   1
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),VFLO   3
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),  VFLO   4
     3 PSI2(50,20),PSI3(50,20),                          NODSAT(20),   VFLO   5
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),       VFLO   6
     5 CPLANT(50,20)                                                   VFLO   7
       COMMON/INF/RINF(50)
C      APPLICATION OF DARCY'S LAW TO FIND FLOW VELOCITIES.             VFLO   8
C      COMPUTE FLOW VELOCITY BETWEEN L-TH AND (L-1)-TH NODES
C      THIS FLOW DEFINED AS INFILTRATION
       PSITOP= (PSI(N,L)+PSI(N,L-1))/2.
       X=PSITOP
       CONTOP=CK(X)
       COND(N,L)=CONTOP
       GRTOP=(PSI(N,L)+DELZ-PSI(N,L-1))/DELZ
       VELZ(N,L)=CONTOP*GRTOP
       RINF(N)=VELZ(N,L)
C      UTILIZATION OF CONDUCTIVITY AT EACH INTERIOR NODE AND TENSION   VFLO   9
C        AT TWO ADJOINING NODES.                                       VFLO  10
C      DOWNWARD VELOCITY DEFINED AS POSITIVE
       DO500J=1,L
       X=PSI(N,J)                                                      VFLO  12
       COND(N,J)=CK(X)                                                 VFLO  13
   500 CONTINUE                                                        VFLO  14
       NN = L - 1                                                      VFLO  15
       DO 700 J = 2,NN                                                 VFLO  16
       M=J+1                                                           VFLO  17
       ZABV=(ZBOTOM/3.28)*100.+(M-1)*DELZ                              VFLO  18
       PHIABV=ZABV+PSI(N,J+1)                                          VFLO  19
       MM=J-1                                                          VFLO  20
       ZBEL=(ZBOTOM/3.28)*100.+(MM-1)*DELZ                             VFLO  21
       PHIBEL=ZBEL+PSI(N,J-1)                                          VFLO  22
       GRAD=(PHIABV-PHIBEL)/(2.*DELZ)                                  VFLO  23
       VELZ(N,J) =  COND(N,J)*GRAD                                     VFLO  24
   700 CONTINUE                                                        VFLO  25
C      COMPUTE NET FLOW BETWEEN 1ST AND 2ND NODES                      VFLO  26
       J=1                                                             VFLO  27
       PSI12=(PSI(N,J)+PSI(N,J+1))/2.                                  VFLO  28
       COND12=CK(PSI12)                                                VFLO  29
       COND(N,J)=COND12                                                VFLO  30
       PHIABV=(ZBOTOM/3.28)*100.+DELZ+PSI(N,J+1)
       PHIBEL=(ZBOTOM/3.28)*100.+PSI(N,J)                              VFLO  31
       GRAD12=(PHIABV-PHIBEL)/DELZ                                     VFLO  32
       QNET12(N)= COND12*GRAD12                                        VFLO  33
       VELZ(N,J)=QNET12(N)                                             VFLO  34
       WRITE (6,800) N
   800 FORMAT ('1',10X,'DOWNWARD VELOCITIES IN CM/MIN AT TIME STEP',I5)
       DO 950 J=1,L
       WRITE (6,900) J,VELZ(N,J)
   900 FORMAT (I5,E8.2)
   950 CONTINUE
       RETURN
       END                                                             VFLO  35
       SUBROUTINE WTABLE(N,L,DELZ,ZBOTOM)                              VFLO  36
C      LOCATES WATER TABLE BASED ON LOCAL FLOW AND                     TABE   1
C        HEAD CONDITIONS                                               TABE   2
       COMMON/ID /PSINCT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),  TABE   3
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),TABE   5
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),    TABE   6
     3 PSI2(50,20),PSI3(50,20),                          NODSAT(20),      TABE   7
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),         TABE   8
     5 QPLANT(50,20)                                                      TABE   9
      COMMON/WTAB/JTAB(50),HTAB(50)
C     ASSUME THAT NODE J=1 CHOSEN LOW ENOUGH SO THAT IT WILL              TABE  10
C     ALWAYS BE SATURATED. FREEZE'S EQ.(12) HOLDS,                        TABE  11
C     SCAN PSI VALUES FOR SATURATION FROM BOTTOM NODE UPWARDS.            TABE  12
      IF (N.EQ.1) HPOND(N)=0.
      NNSAT=1                                                             TABE  13
      DO800J=2,L                                                          TABE  14
      IF(PSI(N,J).GE.0.) NNSAT=NNSAT+1                                    TABE  15
      IF(PSI(N,J).LT.0.) GO TO 900                                        TABE  16
  800 CONTINUE                                                            TABE  17
  900 NODSAT(N)   = NNSAT
      JTAB(N)=NODSAT(N)
      ZTABLE(N)  =ZBOTOM+(NODSAT(N)-1)*DELZ*3.28/100.
      HTAB(N)=JTAB(N)*DELZ*3.28/100.
      IF(NNSAT.EQ.L) ZTABLE(N)   = ZTABLE(N)   + HPOND(N)*3.28/100.       TABE 2
      IF (JTAB(N).EQ.L) HTAB(N)=HTAB(N)+HPOND(N)*3.28/100.
  710 RETURN                                                              TABE  21
      END                                                                 TABE  22
      SUBROUTINE PSIVAL(N,L,DELT,DELZ)                                    PSIV   1
C     COMPUTES VALUES OF PSI IN PROFILE FROM                              PSIV   2
C       RECURSIVE FORMULAS                                                PSIV   3
      COMMON/IO /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),PSIV   5
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),    PSIV   6
     3 PSI2(50,20),PSI3(50,20),                          NODSAT(20),      PSIV   7
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),         PSIV   8
     5 QPLANT(50,20)                                                      PSIV   9
      COMMON/POND/CPOND(50)
C     SET MAXIMUM PONDING DEPTH, IN CENTIMETERS
      PONMAX=5.
C     TWOMAIN CASES ARISE 1) UPPER NODE UNSATURATED OR R K(SAT'D)
C     2) UPPER NODE SATURATED (WITH A FINITE HEAD)                        PSIV  13
C     CASE 2 IS STARTED WHEN R SATURATED K, AND CONTINUES AS LONG AS     PSIV  14
C     CONTINUITY RELATIONSHIPS INDICATE EXISTENCE OF A FINITE PONDING    PSIV  15
C     DEPTH AT THE GROUND SURFACE.                                        PSIV  16
      IF(N.EQ.1) HPOND(N)=0.                                              PSIV  17
      IF (N.EQ.2) HPOND(N)=0.
C     THIS SUBROUTINE GETS CALLED ON 2ND TIME STEP
      IF (N.EQ.2) GO TO 700
      HPOND(N)=HPOND(N-1) + ((RAIN(N-1)-EVAP(N-1))-VELZ(N-1,L))*DELT
      IF (HPOND(N).LT.0.)  HPOND(N)=0.
C     PONDING DEPTH MUST BE NON-NEGATIVE
  700 IF(HPOND(N).GT.0.) GO TO 300                                        PSIV  19
      X=0.                                                                PSIV  20
      CONSAT=CK(X)                                                        PSIV  21
      R=RAIN(N)-EVAP(N)                                                   PSIV  22
C     CHECK 'PREDICTED' VALUE OF PSI AT TOP NODE , IF NOT SATURATED
C     SOLVE CASE 1.
      IF (PSI(N,L).LT.0.)  GO TO 850
      IF (R.GT.CONSAT) HPOND(N)=(R-CONSAT)*DELT
      IF(R.GT.CONSAT) GO TO 300                                           PSIV  23
C-------------------------------------------------
C     SOLVE CASE 1,BELOW.
  850 INDEX=1                                                             PSIV  25
      NDUMMY=999                                                          PSIV  26
      NUNSAT=NDUMMY                                                       PSIV  27
      CALL MATRIX(N,L,INDEX,NUNSAT,DELZ)                                  PSIV  28
      HPOND(N)=0.                                                         PSIV  29
      GO TO 150                                                           PSIV  30
C-----------------------------------------------------------------------PSIV  31
C     SOLUTION OF CASE 2, BELOW                                           PSIV  32
C     SET CONDUCTIVITY AT GROUND EQUAL TO SATURATION VALUE.               PSIV  33
  300 IF (HPOND(N).GT.PONMAX) HPOND(N)=PONMAX
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      PSIGND=HPOND(N)
      PSIGND=AMAX1(0.,PSIGND)
      PSI(N,L)=PSIGND
      INDEX=2
C     SEARCH FOR FIRST UNSATURATED NODE FROM TOP
      DO 400 I=2,L
      K=L-I+1
      IF (PSI(N,K).LT.0.)  GO TO 500
  400 CONTINUE
  500 NUNSAT=K
      IF (NUNSAT.EQ.1)  NUNSAT=999
      CALL MATRIX(N,L,INDEX,NUNSAT,DELZ)
  150 DPOND(N)=HPOND(N)
      RETURN
      END
      SUBROUTINE PSIMID(N,L)
C     COMPUTES VALUES OF PSI(I),PSI(II),PSI(III)
      COMMON/ID /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),
     3 PSI2(50,20),PSI3(50,20),                            NODSAT(20),
     4 CONC(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),
     5 QPLANT(50,20)
      IF (N.EQ.2.) GO TO 510
      DO410J=1,L
      IF (J.EQ.1.) GO TO 610
      IF (J.EQ.L) GO TO 610
      PSI1(N,J)=(PSI(N-1,J)+PSI(N-1,J+1)+PSI(N,J+1)+PSI(N,J))/4.
      PSI2(N,J)=(PSI(N-1,J-1)+PSI(N-1,J)+PSI(N,J)+PSI(N,J-1))/4.
      PSI3(N,J)=(PSI(N-1,J)+PSI(N,J))/2.
      GO TO 410
  610 PSI3(N,J) = (PSI(N-1,J)+PSI(N,J))/2.
      IF (J.EQ.1.) PSI1(N,J)=(PSI(N-1,J)+PSI(N-1,J+1)+PSI(N,J+1)
     1 +PSI(N,J))/4.
      IF(J.EQ.1.) PSI2(N,J) = (PSI(N-1,J)+PSI(N,J))/2.
      IF (J.EQ.L) PSI1(N,J)=(PSI(N-1,J)+PSI(N,J))/2.
      IF(J.EQ.L) PSI2(N,J)=(PSI(N-1,J+1)+PSI(N-1,J)+PSI(N,J)
     1 +PSI(N,J-1))/4.
  410 CONTINUE
      GO TO 715
  510 DO800J=1,L
      IF(J.EQ.1.) GO TO 900
      IF (J.EQ.L) GO TO 900
      PSI1(N,J) = (PSI(N-1,J) + PSI(N-1,J+1))/2.
      PSI2(N,J)=(PSI(N-1,J-1)+PSI(N-1,J))/2.
      PSI3(N,J)= PSI(N-1,J)
      GO TO 800
  900 PSI3(N,J) = PSI(N-1,J)
      IF(J.EQ.1) PSI1(N,J)=(PSI(N-1,J)+PSI(N-1,J+1))/2.
      IF(J.EQ.1) PSI2(N,J)=PSI(N-1,J)
      IF(J.EQ.L) PSI1(N,J)=PSI(N-1,J)
      IF(J.EQ.L) PSI2(N,J)=(PSI(N-1,J-1)+PSI(N-1,J))/2.
  800 CONTINUE
  715 RETURN
      END
      SUBROUTINE SINK(N,L,NOD,DELT,DELZ)
      COMMON/ID /PSINOT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),
     3 PSI2(50,20),PSI3(50,20),                            NODSAT(20),
     4 CONC(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),
     5 QPLANT(50,20)
      COMMON/CROP/ETCROP,WILTM
      COMMON/ROOT/CROOT
      COMMON/MOLE/CMOLD(50)
      COMMON/SOIL/KSOIL
C     COMPUTE 1ST THE DEPTH OF SATURATED SECTION ABOVE DRAIN
C     FROM RESULTS OF PREVIOUS TIME STEP
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      KK=0                                                              SINK 10
C     NOD IS NODE NO AT WHICH DRAIN LOCATED
      NN=NOD+1                                                          SINK 11
      DO500J=NN,L                                                       SINK 12
      IF(PSI(N-1,J).GE.0.) KK=KK+1                                      SINK 13
      IF(PSI(N-1,J).LT.0.)  GO TO 600                                   SINK 14
  500 CONTINUE                                                          SINK 15
  600 HDRAIN=KK*DELZ/100.                                               SINK 16
C     COMPUTE FLOW TO DRAINS (SEE HARRISON), IN METERS/HOUR.            SINK 17
      X=PSI(N-1,NOD)                                                    SINK 18
      SATCON=CK(X)*60./100.                                             SINK 19
      DE=5./3.28
      S=20./3.28
      XLEN=1.                                                           SINK 22
      AREA=XLEN*S                                                       SINK 23
      QDRAIN=4.*SATCON*HDRAIN*(2.*DE+HDRAIN)*XLEN/(S*AREA)              SINK 24
C     FLOW IN CFS/METER BELOW
      QCFSPM=QDRAIN*S*XLEN*0.0098
C     CONVERT TO CFS/FT BELOW
      QCFSPF=QCFSPM/3.28
      QHOLD(N)=QCFSPF
C     CONVERT FROM M/HR TO CM/MIN                                       SINK 25
      QDRAIN=QDRAIN*100./60.                                            SINK 26
C     CONVERT TO (1/MIN)
      QDRAIN=QDRAIN/DELZ
C     NO DRAINS EXIST IN SANDY SOILS OF STUDY AREA
      IF (KSOIL.NE.2) QDRAIN=0.
C     COMPUTE PLANT REQUIREMENTS WITH DEPTH.                            SINK 27
C     TEMPORARILY ASSUMED TO BE ZERO.                                   SINK 28
C     COMPUTE PLANT WITHDRAWALS FOR ALL NODES
C     ASSUME UNIFORM WITHDRAWAL AT TOP HALF OF PROFILE.
C     WITHDRAWAL AT EACH NODE CANNOT EXCEED AVAILABLE MOISTURE.
C     AVAILABLE MOISTURE=MOISTURE CONTENT AT NODE (USE VALUE FROM
C        LAST TIME PERIOD) MINUS CONTENT AT WILTING POINT
C     COMPUTE WITHDRAWALS AT EACH NODE
      LROOT=DROOT*30.5/DELZ
      LLOW=L-LROOT
      IF (LLOW.LT.1)  LLOW=1
      DO 700 J=1,L
      IF (J.LT.LLOW)  GO TO 750
      QAVAIL=(THETA(N-1,J)/100. - WILTM) / DELT
      QP=ETCROP/FLOAT(LROOT)
C     CONVERT TO (1/MIN)
      QP=QP/DELZ
      IF (QP.GT.QAVAIL)  QP=QAVAIL
      QPLANT(N,J)=QP
      GO TO 700
  750 QPLANT(N,J)=0.
  700 CONTINUE
      DO850J=1,L                                                        SINK 32
      QSINK(N,J)=QPLANT(N,J)                                            SINK 33
      IF(J.EQ.NOD) QSINK(N,J)=QPLANT(N,J) + QDRAIN                      SINK 34
C     SINK UNITS (1/MIN)
  850 CONTINUE                                                          SINK 35
      RETURN                                                            SINK 36
      END                                                               SINK 37
      SUBROUTINE  MATRIX(N,L,INDEX,NUNSAT,DELZ)                         MATR  1
      COMMON/IO /PSINCT(50),RAIN(20),EVAP(20),GWFLOW(20),ZTABLE(20),
     1 PSI(50,20),A(50,20),B(50,20),C(50,20),D(50,20),E(50,20),F(50,20),MATR  3
     2 CSLOPE(50,20),THETA(50,20),THENOT(50),VELZ(50,20),PSI1(50,20),   MATR  4
     3 PSI2(50,20),PSI3(50,20),                      NODSAT(20),        MATR  5
     4 COND(50,20),PSIBOT(50),HPOND(50),QSINK(50,20),QNET12(50),        MATR  6
     5 QPLANT(50,20)                                                    MATR  7
      DIMENSION  XL(50,20),RHS(50)                                      MATR  8
C     USES GAUSSIAN TECHNIQUE TO COMPUTE PSI VALUES RECURSIVELY.        MATR  9
C     INITIALIZE LEFT HAND SIDE ARRAY (XL)                              MATR 10
      DO550I=1,L                                                        MATR 11
      DO520J=1,L                                                        MATR 12
      XL(I,J)=0.
  520 CONTINUE
  550 CONTINUE
C     INSERT VALUES INTO RIGHT HAND SIDE ARRAY (RHS)
      DO600J=1,L
      I=J
      RHS(I)=D(N,J)
  600 CONTINUE
C     INSERT VALUES OF A,B,C INTO LEFT HAND SIDE
C     ARRAY (XL)
      I=1
      JNOCE=I
      XL(I,I)=B(N,JNOCE)
      XL(I,I+1)=-A(N,JNODE)
      M=L-1
      CO660I=2,M
      JNCCE=I
      XL(I,I-1)=-C(N,JNODE)
      XL(I,I)=B(N,JNOCE)
      XL(I,I+1)=-A(N,JNODE)
  660 CONTINUE
      I=L
      JNODE=I
      XL(I,I-1)=-C(N,JNODE)
      XL(I,I)=B(N,JNOCE)
C     WRITE (6,1400) N
 1400 FORMAT ('1',5X,'TIME STEP=',I5)
      CO 1500 I=1,L
C     WRITE (6,2000) (XL(I,J),J=1,L)
 2000 FORMAT (5X,10F6.2)
 1500 CONTINUE
      I=1
      J=1
      XDENOM=XL(1,1)
      WRITE (6,1800) I,J,XL(I,J)
 1800 FORMAT (2I5,F6.2)
      CO750J=1,L
      XL(I,J)=XL(I,J)/XDENOM
  750 CONTINUE
      RHS(I)=RHS(I)/XCENOM
      CO1000I=2,L
      J=I-1
      FACTOR=-XL(I,J)/XL(J,J)
C     WRITE (6,1900) J,XL(J,J)
 1900 FORMAT (I5,F5.2)
      IPREV=I-1
      CO800J=1,L
C     IF (I.EQ.10)  WRITE (6,1850) (XL(I,J),J=1,L)
 1850 FORMAT (10F6.3)
C     IF (I.EQ.10)  WRITE (6,1950) FACTOR
 1950 FORMAT ('  FACTCR AT 10=',F6.2)
C     IF (I.EQ.10)  WRITE (6,1850)  (XL(IPREV,J),J=1,L)
      XL(I,J)=XL(I,J)+XL(IPREV,J)*FACTOR
C     IF (I.EQ.10)  WRITE (6,1850) (XL(I,J),J=1,L)
  800 CONTINUE
      RHS(I)=RHS(I)+RHS(IPREV)*FACTOR
      J=I
      XDENOM=XL(I,J)
C     WRITE (6,1800) I,J,XL(I,J)
      CO900J=1,L
      XL(I,J)=XL(I,J)/XDENOM
  900 CONTINUE
      RHS(I)=RHS(I)/XCENOM
 1000 CONTINUE
C     CO 1700 I=1,L
C     WRITE (6,2000) (XL(I,J),J=1,L)
C1700 CONTINUE
C     COMPUTE VALUE OF PSI(N,L)-
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      I=L                                                               MATR 81
C     WRITE(6,2700) INDEX                                               MATR 82
 2700 FORMAT(2X,'INDEX=',I3)                                            MATR 83
      IF (INDEX.EQ.1)  PSI(N,I)=RHS(I)                                  MATR 84
      IF (INDEX.EQ.2)   PSI(N,I)=PSI(N,I)                               MATR 85
C     COMPUTE VALUES OF PSI RECURSIVELY                                 MATR 86
      LL=L-1                                                            MATR 87
      DO570I=1,LL                                                       MATR 88
      K=L-I+1                                                           MATR 89
      JNODE=K                                                           MATR 90
      JNODE1=JNODE-1                                                    MATR 91
C     IF (JNODE1.EQ.NUNSAT)  GO TO 580                                  MATR 92
      PSI(N,JNODE-1)=RHS(K-1)-XL(K-1,K)*PSI(N,JNODE)                    MATR 93
      GO TO 570                                                         MATR 94
C     PREVIOUS STATEMENTS APPLYING DARCY'S LAW TO 1-ST UNSATURATED NODE
C     DIRECTLY HAVE BEEN DELETED
  570 CONTINUE                                                          MATR102
      RETURN                                                            MATR103
      END                                                               MATR104
      FUNCTION TENS(Y)                                                  STEN  1
C     TENSION VERSUS MOISTURE CONTENT RELATIONSHIPS                     STEN  2
C     FORMULAS BELOW FOR SANDY SOILS                                    STEN  3
      IF (Y.LT.9.5) GC TO 600                                           STEN  4
      IF (Y.GT.42.) GO TO 610                                           STEN  5
      TENS =-EXP((131.456-Y)/27.4112)                                   STEN  6
      GO TC 620                                                         STEN  7
  600 TENS =-EXP((13.6879-Y)/0.9433)                                    STEN  8
      GO TC 620                                                         STEN  9
  610 TENS =-EXP((42.5178-Y)/0.1335)                                    STEN 10
      IF (Y.GE.43.3)  TENS=0.
  620 RETURN                                                            STEN 11
      END                                                               STEN 12
      FUNCTION CK(X)                                                     SCK  1
C     CONDUCTIVITY VERSUS PSI RELATIONSHIPS                              SCK  2
C     FORMULAS BELOW FOR SANDY SOILS                                     SCK  3
      IF (X.GE.0.)  GO TO 315                                            SCK  4
      Q=ABS(X)                                                           SCK  5
      IF (Q.LT.50.) GO TO 700                                            SCK  6
      IF (Q.GT.150.) GO TO 710                                           SCK  7
      CK = 0.5391 - 0.1056*ALOG(Q)                                       SCK  8
      GO TC 720                                                          SCK  9
  700 CK = 0.1264 - 0.00009242*ALOG(Q)                                   SCK 10
      GO TC 720                                                          SCK 11
  710 CK = 0.01117 - 0.0002381*ALOG(Q)                                   SCK 12
  720 RETURN                                                             SCK 13
  315 CK=0.126                                                           SCK 14
      RETURN                                                             SCK 15
      END                                                                SCK 16
      FUNCTION CSL(X)                                                   SCSL  1
C     C (DTHETA/DPSI) VERSUS PSI RELATIONSHIPS                          SCSL  2
C     FORMULAS BELOW FOR SANDY SOILS                                    SCSL  3
      IF (X.GE.0.)  GC TO 535                                           SCSL  4
      P=ABS(X)                                                          SCSL  5
      IF (P.LT.25.) GO TO 500                                           SCSL  6
      IF (P.GT.85.) GO TO 510                                           SCSL  7
      CSL = (27.4112/P)/100.
      GO TC 520                                                         SCSL  9
  500 IF (P.LE.1.)  GO TO 535                                           SCSL 10
      CSL = (0.1335/P )/100.
      GO TG 520                                                         SCSL 12
  510 CSL = (0.9433/P )/100.
      GO TO 520                                                         SCSL 14
  535 CSL=0.                                                            SCSL 15
  520 RETURN                                                            SCSL 16
      END                                                               SCSL 17
      FUNCTION HUMID(X)                                                 SHUM  1
C     COMPUTES MOISTURE CONTENT FOR A GIVEN PSI.                        SHUM  2
C     FORMULAS BELOW FOR SANDY SOIL.                                    SHUM  3
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      IF (X.GE.0.)  GC TO 830                                           SHUM   4
      S=ABS(X)                                                          SHUM   5
      IF (S.LT.26.)  GO TO 815                                          SHUM   6
      IF (S.GT.86.)  GO TO 825                                          SHUM   7
      HUMIC=131.45-27.41*ALOG(S)                                        SHUM   8
      RETURN                                                            SHUM   9
  815 IF (S.LE.1.)  GO TO 830                                           SHUM  10
      HUMIC=42.51 - 0.1335*ALOG(S)                                      SHUM  11
      RETURN                                                            SHUM  12
  825 HUMIC=13.68 - 0.94*ALOG(S)                                        SHUM  13
      IF (HUMIC.LT.0.)  HUMID=0.                                        SHUM  14
      RETURN                                                            SHUM  15
  830 HUMIC=43.3                                                        SHUM  16
      RETURN                                                            SHUM  17
      ENC                                                               SHUM  18
      SUBROUTINE GRAPH(NPLOT,KKK,NSTEPS,NCURVE,G,TIT)
C     ROUTINE TO MAKE PLOTS OF OUTPUT.  WRITTEN BY WRE.
C     ARRAY G CONTAINS AN X VALUE, THEN CORRESPONDING Y VALUES, THEN X ETC.
C     NCURVE=NUMBER OF Y VALUES TO BE PLOTTED FOR EACH X VALUE.
      DIMENSION X(101,10),Y(101,10),NLOC(50),NPT(50),G(603)
      CIMENSION TIT(20)
      COMMCN/LAB/ TITLE(20),XLAB(11),YLAB(6),HORIZ(20),VERT(6)
      CALL ERRSET (208,300,5,C,0,209)
      IF (KKK.GT.1) GC TO 110
      CC 115 I=1,20
  115 TITLE(I) = TIT(I)
  110 MC=NSTEPS/100
      IF(MC*100.NE.NSTEPS) MC=MC+1
      N=1
      NR=0
      L=1
      CO 300 K=1,NSTEPS,MC
      N=N+1
      CO 290 J=1,MC
      NR=NR+1
      IF(NR.GT.NSTEPS) GO TO 290
      TIMES=G(L)
      CO 280 M=1,NCURVE
      LL=L+M
  280 Y(N,M)=G(LL)
      L=L+NCURVE+1
  290 CCNTINUE
      CO 295 M=1,NCURVE
C     LEAVE ABSCISSA VALUES (TIMES) IN SECONDS.
  295 X(N,M)=TIMES
  300 CCNTINUE
      CO 320 M=1,NCURVE
      NPT(M)=N
      X(1,M)=0.
      Y(1,M)=0.
  320 CONTINUE
      CALL CURVE(X,Y,NPT,NCURVE,NPLOT)
      RETURN
      ENC
      SUBROUTINE PINE(X1,Y1,X2,Y2,NSYM,NCT)
      AXA=X1
      AXB=X2
      AYA=Y1
      AYB=Y2
      N=1
      IF(ABS(AXB-AXA).LT.ABS(AYB-AYA)) GO TO 290
C
C     SET PARAMETERS FOR X DIRECTION
C
      IF(AXB.GT.AXA) GO TO 245
      AXA=X2
      AXB=X1
      AYA=Y2
      AYB=Y1
  245 CONTINUE
      IXA=AXA+.5
      IXB=AXB+.5
      IYA=AYA+.5
      IYB=AYB+.5
  250 CONTINUE
      IF(IXA.LT.0.OR.IXA.GT.100) GO TO 260
      IF(IYA.LT.0.OR.IYA.GT.50) GO TO 260
      CALL PPLOT(IXA,IYA,NSYM,NCT)
  260 CONTINUE
      IXA=IXA+1
      YA=(N*(AYB-AYA))/(AXB-AXA)
      IYA=AYA+YA+0.5
      N=N+1
      IF(IXA.LE.IXB) GO TO 250
      GO TO 400
C
C     SET PARAMETERS FOR Y DIRECTION
C
  290 CONTINUE
      IF(AYB.GT.AYA)   GO TO 295
      AYB=Y1
      AYA=Y2
      AXB=X1
      AXA=X2
  295 CONTINUE
      IXA=AXA+.5
      IXB=AXB+.5
      IYA=AYA+.5
      IYB=AYB+.5
  300 CONTINUE
      IF(IXA.LT.0.OR.IXA.GT.100) GO TO 310
      IF(IYA.LT.0.OR.IYA.GT.50) GO TO 310
      CALL PPLOT(IXA,IYA,NSYM,NCT)
  310 CONTINUE
      IYA=IYA+1
      XA=(N*(AXB-AXA))/(AYB-AYA)
      IXA=XA+AXA+0.5
      N=N+1
      IF(IYA-IYB) 300,320,400
  320 IXA = IXB
      GO TO 300
  400 RETURN
      END
      SUBROUTINE CURVE (X,Y,NPT,NCV,NPLOT)
      DIMENSION X(101,10),Y(101,10),NPT(10)
      COMMON/LAB/ TITLE(20),XLAB(11),YLAB(6),HORIZ(20),VERT(6)
      IZ=0
      IZA=0
      XMAX=X(1,1)
      XMIN=XMAX
      YMIN=Y(1,1)
      YMAX=YMIN
      DO 205 L=1,NCV
      NPTM=NPT(L)
      IF(NPTM.EQ.0) GO TO 205
      DO 204 N=1,NPTM
      IF(X(N,L).LT.XMIN) XMIN=X(N,L)
      IF(X(N,L).GT.XMAX) XMAX=X(N,L)
      IF(Y(N,L).LT.YMIN) YMIN=Y(N,L)
      IF(Y(N,L).GT.YMAX) YMAX=Y(N,L)
  204 CONTINUE
  205 CONTINUE
      RANGE=(YMAX-YMIN)/5.
      A = ALOG10(RANGE)
      IF(A.LT.0.) GO TO 220
      N=A
      RANGE=RANGE/(10.**N)
      L=RANGE+1.001
  206 CONTINUE
      IF(L.EQ.2) GO TO 209
      IF(L.GT.4) GO TO 207
      L=4
  207 IF(L.GT.5) L=10
  209 CONTINUE
      FRANG=L*10.**N
      GO TO 240
  220 M=A-0.9999
      N=-M
      RANGE=RANGE*10.**N
      L=RANGE+1.001
  226 CONTINUE
      IF(L.EQ.2) GO TO 229
      IF(L.GT.4) GO TO 227
      L=4
  227 CONTINUE
      IF(L.GT.5) L=10
  229 CONTINUE
      FRANG=L/10.**N
  240 CONTINUE
      K=YMIN/FRANG
      IF(YMAX.LE.(K+5)*FRANG) GO TO 250
      L=L+1
      IF(L.LT.11) GO TO 245
      L=2
      N=N+1
  245 CONTINUE
      IF(A) 226,206,206
  250 YMIN=K*FRANG
      YMAX=(K+5)*FRANG
      XSCAL=100./(XMAX-XMIN)
      YSCAL=50./(YMAX-YMIN)
      XINT=(XMAX-XMIN)/10.
      YINT=(YMAX-YMIN)/5.
      XLAB(1) =XMIN
      DO 260 N=1,10
  260 XLAB(N+1)=XLAB(N)+XINT
      YLAB(6)=YMIN
      DO 270 N=1,5
  270 YLAB(6-N)=YLAB(7-N)+YINT
      NLA=100
      CALL PPLOT(IZ,IZA,NLA,NPLOT)
      K = 1
      DO 450 L=1,NCV
       IF(NPT(L).EQ.0) GO TO 440
      XO=XSCAL*(X(1,L)-XMIN)
      YO=YSCAL*(Y(1,L)-YMIN)
      NPOINT = NPT(L)
      DO 400 N = 2,NPOINT
      XT = XSCAL*(X(N,L) - XMIN)
      YT = YSCAL*(Y(N,L) - YMIN)
      CALL PINE(XO,YO,XT,YT,K,NPLOT)
      XO = XT
      YO = YT
  400 CONTINUE
  420 CONTINUE
  440 K = K + 1
      IF(K.EQ.7) K = 1
  450 CONTINUE
      NLA=99
      CALL PPLOT(IZ,IZA,NLA,NPLOT)
      RETURN
      END
      SUBROUTINE PPLOT(IX,IY,K,NCT)
      DIMENSION A(51,101), SYM(9)
      COMMON/LAB/ TITLE(20),XLAB(11),YLAB(6),HORIZ(20),VERT(6)
      DATA SYM / 4H****, 4H++++, 4H'''', 4HXXXX, 4H...., 4H2222,
     .           4H    , 4HIIII, 4H---- /
      IF(K-99) 200,220,230
  200 A(51-IY,IX+1)=SYM(K)
      RETURN
  220 CONTINUE
      I=0
      WRITE (6,103) TITLE,NCT
      DO 225 II=1,6
      I=I+1
      WRITE(6,101) YLAB(II),(A(I,J),J=1,101)
      IF(II.EQ.6) GO TO 228
      DO 224 JJ=1,9
      I=I+1
      IF(I.NE.28) GO TO 221
      WRITE(6,106) VERT(5),VERT(6),(A(I,J),J=1,101)
      GO TO 224
  221 CONTINUE
      IF(I.NE.24) GO TO 222
      WRITE(6,106) VERT(1),VERT(2),(A(I,J),J=1,101)
      GO TO 224
  222 IF(I.NE.26) GO TO 223
      WRITE(6,106) VERT(3),VERT(4),(A(I,J),J=1,101)
      GO TO 224
  223 CONTINUE
      WRITE(6,100)(A(I,J),J=1,101)
  224 CONTINUE
  225 CONTINUE
  228 CONTINUE
      WRITE(6,102) XLAB
      WRITE(6,105) HORIZ
  100 FORMAT(18X,101A1)
  101 FORMAT(F17.3,1X,101A1)
  102 FORMAT(F20.1,10F10.1)
  103 FORMAT (1H1,16X,20A4,10X,'ELEMENT NUMBER',I4)
  105 FORMAT(/40X,10A4)
  106 FORMAT(3X,2A4,7X,101A1)
  230 DO 250 I=1,50
      DO 240 J=1,101
  240 A(I,J)=SYM(7)
      A(I,1)=SYM(8)
      A(I,101)=SYM(8)
  250 CONTINUE
      DO 260 J=1,101
  260 A(51,J)=SYM(9)
      DO 270 I=1,101,10
  270 A(51,I)=SYM(8)
      DO 290 I=11,41,10
      A(I,1)=SYM(9)
      A(I,101)=SYM(9)
  290 CONTINUE
      RETURN
      END
      FUNCTION ACOS(X)
      ARG = (1.0 - X) / (1.0 + X)
      TARG = SQRT(ARG)
      ACOS = 2.0 * ATAN(TARG)
      RETURN
      END
      SUBROUTINE SOILQU                                                 SLQU   1
C     PROGRAM 'SOILQUAL'                                                SLQU   2
C     ------------------                                                SLQU   3
C                                                                       SLQU   4
C     PERFORMS WATER QUALITY COMPUTATIONS AT THE                        SLQU   5
C     UNSATURATED SOIL ZONE.  PROCESSES CONSIDERED ARE                  SLQU   6
C     ADVECTION, DISPERSION, ABSORPTION AND RELEASE                     SLQU   7
C     OF SUBSTANCES BY THE SOIL.  FINITE DIFFERENCE
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C     EQUATIONS UTILIZE PREVIOUSLY COMPUTED VELOCITIES                 SLQU   8
C     AT EVERY NODE IN SOIL PROFILE.  AT EACH TIME                     SLQU   9
C     STEP, PROGRAM COMPUTES CONCENTRATION OF                          SLQU  10
C     SUBSTANCE(S) AT EACH NODE.  TRIDIAGONAL MATRIX                   SLQU  11
C     SCHEME IS USED.  INTERFACES WITH 'INFILT' PROGRAM.               SLQU  12
C-------------------------------------------------------------         SLQU  13
C          PARTIAL LIST OF VARIABLES--                                 SLQU  14
C     NNODES=NO. OF NODES IN SOIL PROFILE                              SLQU  15
C     NSTEPS=NO. OF TIME STEPS IN PERIOD OF STUDY                      SLQU  16
C     CELT=TIME INTERVAL                                               SLQU  17
C     DELZ=VERTICAL INTERVAL SPACING                                   SLQU  18
C     TSTART=STARTING TIME OF PERIOD OF ANALYSIS                       SLQU  19
C     TEND=ENDING TIME OF PERIOD OF ANALYSIS                           SLQU  20
C     FERT(N)=FERTILIZER INPUT OF N AT N-TH TIME STEP                  SLQU  21
C     FERTP(N)=FERTILIZER INPUT OF P AT N-TH TIME STEP                 SLQU  22
C     RAIN(N)=RAINFALL RATE AT N-TH TIME STEP                          SLQU  23
C     EVAP(N)=EVAPORATION  RATE AT N-TH TIME STEP                      SLQU  24
C     GWFLOW(N)=GROUNDWATER FLOW AT BOTTOM NODE AT N-TH TIME STEP      SLQU  25
C     SOUN=AVERAGE (TEMPORAL AND SPATIAL) SOIL RELEASE OF NITRATE-N
C          IN (LB/FT-MONTH-ACRE)
C     SOUP=AVERAGE SOIL RELEASE OF TOTAL INORGANIC PHOSPHOROUS
C          IN (LB/FT-MONTH-ACRE)
C     SINN=AVERAGE SOIL UPTAKE OF NITRATE-N
C          IN (LB/FT-MONTH-ACRE)
C     SINP=AVERAGE SOIL UPTAKE OF TOTAL INORGANIC PHOSPHOROUS
C          IN (LB/FT-MONTH-ACRE)
C     SOURN(N,L)=RATE OF N RELEASE BY SOIL AT N-TH TIME STEP;L-TH NODE SLQU  26
C               IN LB/MONTH                                            SLQU  27
C     SOURP(N,L)=RATE OF P RELEASE BY SOIL AT N-TH TIME STEP;L-TH NODE SLQU  28
C               IN LB/MONTH                                            SLQU  29
C     SINKN(N,L)=RATE OF N UPTAKE BY SOIL AT N-TH TIME STEP,L-TH NODE  SLQU  30
C               IN LB/MONTH                                            SLQU  31
C     SINKP(N,L)=RATE OF P UPTAKE BY SOIL AT N-TH TIME STEP,L-TH NODE  SLQU  32
C               IN LB/MONTH                                            SLQU  33
C     VELZ(N,L)=FLOW VELOCITY AT N-TH TIME STEP,L-TH NODE              SLQU  34
C     SMOIST=SATURATED MOISTURE CONTENT                                SLQU  35
C     VMAX=VOLUME AT SATURATION                                        SLQU  36
C     PSI(N,L)=PRESSURE AT N-TH TIME STEP,L-TH NODE                    SLQU  37
C     C(M,N,L)=CONCENTRATION OF M-TH SUBSTANCE AT N-TH TIME STEP,      SLQU  38
C               L-TH NODE  (IN MG/L)                                   SLQU  39
C     CKD(N,L)=DISPERSION COEFFICIENT FOR N-TH TIME STEP,L-TH NODE     SLQU  40
C               IN (SQ CM/MIN)                                         SLQU  41
C     CROP(N)=CROP TYPE GROWN AT N-TH TIME STEP                        SLQU  42
C     THETA(N,L)=MOISTURE CONTENT AT N-TH TIME STEP,L-TH NODE          SLQU  43
C     VISKIN=KINEMATIC VISCOSITY OF WATER                              SLQU  44
C     ALPHA3=COEFFICIENT USED TO COMPUTE DISPERSION COEFFICIENT        SLQU  45
C               (SEE REDDELL,P.16)                                     SLQU  46
C     BETA3=COEFFICIENT ALSO USED IN DISPERSION COEFFICIENT FORMULA;   SLQU  47
C               AS ABOVE                                               SLQU  48
C     COND(N,L)=HYDRAULIC CONDUCTIVITY (LENGTH/TIME) FOR               SLQU  49
C               N-TH TIME STEP,L-TH NODE                               SLQU  50
C     CONV=FACTOR USED TO CONVERT COND (CM/MIN) TO
C               PERMEABILITY UNITS (SQ CM) = 1.91E-7                   SLQU  52
C     CPER(N,L)=PERMEABILITY IN UNITS OF (LENGTH**2)                   SLQU  53
C               HERE,SQ CM                                             SLQU  54
C     AC(N,L)=COEF FOR CONCENTRATION AT UPPER NODE,                    SLQU  55
C               N-TH TIME STEP AT L-TH NODE                            SLQU  56
C     BC(N,L)=COEF FOR CONCENTRATION AT MIDDLE NODE,                   SLQU  57
C               N-TH TIME STEP AT L-TH NODE                            SLQU  58
C     CC(N,L)=COEF FOR CONCENTRATION AT LOWER NODE,                    SLQU  59
C               N-TH TIME STEP AT L-TH NODE                            SLQU  60
C     DC(N,L)=TERM FOR KNOWN VALUES,                                   SLQU  61
C               N-TH TIME STEP AT L-TH NODE                            SLQU  62
C     BFLUX(N)=FLUX AT BOTTOM NODE AT N-TH TIME STEP                   SLQU  63
C               IN LB/AC/YEAR
C     CFACT1=CONV FACTOR FROM LB/MO-ACRE TO MG/MIN-ACRE=10.35
C     CFACT2=CONV FACTOR FROM (DELZ(CM)*1ACRE) TO LITERS=4.05*(10**4)  SLQU  66
C     CFL=CONV FACTOR FROM (CM/MIN)*(MG/L) TO (LB/AC/MIN)              SLQU  67
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C                 =8.90*(10**-2)
C        CYEAR=CONV FACTOR FROM (CM/MIN)*(MG/L) TO (LB/ACRE-YR) = 4.70E03    SLCU 68
C        KMONTH=MONTH IN WHICH SIMULATION TAKES PLACE
C        K=INDEX DENOTING MONTH                                               SLQU 69
C        CINIT(L)=INITIAL CONCENTRATION AT L-TH NODE                          SLQU 70
C        FSAT=FRACTION OF SATURATION (PERCENT/100.)                           SLCU 71
C        DROOT=DEPTH OF ROOT ZONE (FT)
C        UNIT=UPTAKE RATE OF N BY PLANTS (LB/AC-YR)
C        UPHOS=UPTAKE RATE OF P BY PLANTS (LB/AC-YR)
C        CMOLD(M,N)=CONC. OF M-TH POLLUTANT AT MOLE DRAIN AT STEP N
C        CTABLE=CONCENTRATION OF SUBSTANCE AT WATER TABLE NODE
C-----------------------------------------------
C        SET UP COMMON STORAGE AREAS                                          SLQU 72
         COMMON/IC     /NNODES,NSTEPS,DELT,DELZ,TSTART,TEND,FERTN(50),        SLCU 73
        1 FERTP(50),RAIN(50),EVAP(50),GWFLOW(50),SOURN(50,20),                SL
        2 ,SINKN(50,20),SINKP(50,20),VELZ(50,20),SMOIST,PSI(50,20),SOURP(50,20) SLQU 75
        3 C(2,50,20),CROP(50),THETA(50,20),VISKIN,ALPHA3,BETA3,COND(50,20),   SLQU 76
        4           AC(50,20),BC(50,20),CC(50,20),DC(50,20),BFLUX(50),CFL     SLCU 77
        5,CONV,K,L,M ,CPER(50,20),CKD(50,20),CFACT1,CFACT2,N,CINIT(50)        SLCU 78
        6 ,CYEAR                                                              SLQU 79
         COMMON/MOLE/CMOLD(50)
         COMMON/SOIL/KSOIL
         COMMON/CMOLE/CMOLD(2,50)
         COMMON/LOCMOL/LMOLE
         COMMON/HTAB/JTAB(50),HTAB(50)
         COMMON/CTAB/CTABLE(2,50)
         COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
        1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
        2 NRERE2,NOVRE3
C------------------------------------------------------------
         NUNIF3=14                                                            SLQU 80
C***     READ (NUNIF3)DELZ,DELT,NSTEPS,NNODES,DROOT
         DELZ=6.7
         DELT=10
         NSTEPS=15
         NNODES=10
         DROOT=0.
         NMONTH=12
         KMONTH=7
C        READ IN DATA                                                         SLCU 88
         READ (5,100) (FERTN(K),K=1,NMONTH)                                   SLCU 89
  100    FORMAT (12F5.2)                                                      SLCU 92
         READ (5,100)(FERTP(K),K=1,NMONTH)                                    SLQU 93
         READ (5,105) SOUN,SOUP,SINN,SINP                                     SLCU 94
  105    FORMAT (4F5.2)                                                       SLCU 95
         READ (5,130)  (CROP(K),K=1,NMONTH)
  130    FORMAT (12F5.2)                                                      SLCU123
         READ (5,140) VISKIN,ALPHA3,BETA3                                     SLCU124
  140    FORMAT (3F10.5)                                                      SLQU125
C        'CONV' BELOW IN SQ CM                                                SLQU126
         READ (5,150) SMOIST,VMAX,CFL,CONV,CFACT1,CFACT2 ,CYEAR               SLCU127
  150    FORMAT (2F10.5,F10.4,F10.9,F10.5,F10.4,F10.2)                        SLCU128
         READ (5,160) (CINIT(L),L=1,NNODES)                                   SLCU129
  160    FORMAT (10F5.2)                                                      SLQU130
C        INITIALIZE AT ZEROS, ABOVE, EXCEPT TOP NODE                          SLCU131
C        EVENTUALLY MIGHT NEED ONE INITIAL CONCENTRATION VECTOR
C        FOR EACH SUBSTANCE
         READ (5,165) UNIT,UPHOS
  165    FORMAT (2F5.2)
C-------------------------------------
         WRITE (6,700) DELZ,DELT                                              SLQU132
  700    FORMAT (' SPACING IN CM',F7.2,'TIME STEP IN MIN ',F7.2)
C        CONVERT SATURATION MOISTURE VALUE FROM PERCENT TO FRACTION
         SMOIST=SMOIST/100.
         K=KMONTH
C        CONVERT FROM 'PER FT' TO 'PER NODE' BASIS                            SLQU135
C        COULD MULTIPLY VALUES BELOW BY SEASONAL AND SPATIAL FACTORS
         L=1
```

```
      SOURN(K,L)=SOUN*CELZ*0.5/30.5
      SCURP(K,L)=SOUP*CELZ*C.5/30.5
      SINKN(K,L)=SINN*CELZ*0.5/30.5
      SINKP(K,L)=SINP*DELZ*0.5/30.5
      NN1=NNODES-1
      CC 850 L=2,NN1
      SOURN(K,L)=SOUN*CELZ    /30.5
      SCURP(K,L)=SOUP*DELZ    /30.5
      SINKN(K,L)=SINN*CELZ    /30.5
      SINKP(K,L)=SINP*CELZ    /30.5
  850 CONTINUE
      L=NNCDES
      SOURN(K,L)=SOUN*CELZ*0.5/30.5
      SCURP(K,L)=SOUP*CELZ*0.5/30.5
      SINKN(K,L)=SINN*CELZ*0.5/30.5
      SINKP(K,L)=SINP*CELZ*0.5/30.5
C     CCMPUTE N ANC P UPTAKE BY PLANTS AT NODES WITHIN ROOT ZONE
      NRCCT=DRCOT*30.5/DELZ
      NLCWER=NNODES-NRCOT
      IF (NLOWER.LT.1) NLOWER=1
      CO 185 L=NLOWER,NNOCES
      IF (NLOWER.EQ.10) GO TO 185
      SINKN(K,L)=SINKN(K,L)+(UNIT/12.)*DELZ/(DROOT*30.5)
      SINKP(K,L)=SINKP(K,L)+(UPHOS/12.)*DELZ/(DROOT*30.5)
  185 CONTINUE
      CC 170 N=1,NSTEPS                                                  SLQU136
      CO 180 L=1,NNODES                                                  SLCU137
C     CCMPUTE SOURCE AND SINK TERMS FOR EVERY TIME STEP WITHIN           SLCU133
C     THE MONTH IN QUESTION                                              SLQU134
C     RATE UNITS BELOW ARE LB/MO-ACRE                                    SLQU138
      SOURN(N,L)=SOURN(K,L)                                              SLCU139
      SCURP(N,L)=SCURP(K,L)                                              SLCU140
      SINKN(N,L)=SINKN(K,L)                                              SLCU141
      SINKP(N,L)=SINKP(K,L)                                              SLQU142
  180 CONTINUE                                                           SLCU143
  170 CONTINUE                                                           SLCU144
C     FOR ALL TIME STEPS, COMPUTE THE VALUES OF                          SLCU145
C     VARIABLES TO BE USED IN FINITE DIFFERENCE FORMULATION              SLCU146
C     NOTE--PRESENTLY, VALUES OF 'SOURN','SOURP','SINKN' AND'SINKP'      SLCU147
C     ARE READ IN.  INSTEAC, THESE COULD BE COMPUTED USING FUNCTIONAL    SLCU148
C     RELATIONSHIP (E.G.,SINUSOIDAL) INVOLVING MIN AND MAX VALUES.       SLCU149
C                                                                        SLCU150
C     COMPUTE DISPERSICN COEFFICIENTS BELOW--                            SLCU151
C     VISKIN=0.00001040 (BASED ON ORLANDO,FLA. MEAN TEMP 71.5 F)         SLCU152
C                   IN (SQ FT/SEC)                                       SLCU153
C     CONVERT  VISKIN FROM (SQ FT/SEC) TO (SQ CM/SEC)                    SLQU154
      VISKIN=VISKIN*0.001075
      CO 210 N=1,NSTEPS
C***  REAC (NUNIF3)(CCND(N,L),L=1,NNODES)
C     TEMPORARY VALUES BELOW
  210 CONTINUE
      CO 220 N=1,NSTEPS
C***  REAC (NUNIF3)(VELZ(N,L),L=1,NNODES)
  220 CONTINUE
      CO 230 N=1,NSTEPS
C***  REAC (NUNIF3)(THETA(N,L),L=1,NNODES)
C***  THETA(N,L)=THETA(N,L)/100.
  230 CONTINUE
C**   READ (NUNIF3)(QMCLD(N),N=1,NSTEPS)
C**   REWIND NUNIF3
C***  TEMPORARY LOOP FOR SETTING VALUES
      CO 375 N=1,NSTEPS
      CO 375 L=1,NNODES
      CONC(N,L)=0.18
      VELZ(N,L)=0.18
      THETA(N,L)=0.80
      QMOLC(N)=0.
  375 CONTINUE
```

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      DO 200 N=1,NSTEPS                                                 SLCU157
      DO 250 L=1,NNODES                                                 SLCU158
C     NOTES--                                                           SLCU163
C     ALPHA3=88 FOR SAND                                                SLCU164
C     BETA3=1.2  (HOOPES AND HARLEMAN,1965)                             SLCU165
C     BELOW, CONVERT HYDRAULIC CONDUCTIVITIES TO APPROPRIATE            SLCU166
C     UNITS OF PERMEABILITY (FROM CM/MIN TO SQ CM)                      SLCU167
      CPER(N,L)=COND(N,L)*CONV                                          SLCU168
      TERM1=VISKIN*ALPHA3                                               SLCU169
C     CONVERT VELOCITY FROM CM/MIN TO CM/SEC
      VZ=VELZ(N,L)/60.
      VZ=ABS(VZ)
      TERM2=VZ       *(CPER(N,L)**0.5)/VISKIN                           SLCU170
      IF (TERM2.LE.0.)  GO TO 235
C     'CKD' BELOW SHOULD BE IN (SQ CM/SEC).                             SLCU171
      CKD(N,L)=TERM1*(TERM2)**BETA3                                     SLCU172
      GO TO 245
  235 CKD(N,L)=0.
C     CONVERT DISPERSION COEF FROM SQ CM/SEC TO SQ CM/MIN
  245 CKD(N,L)=CKD(N,L)*60.
  250 CONTINUE                                                          SLCU173
  200 CONTINUE                                                          SLCU174
C     PREPARE FINITE DIFFERENCE RELATIONSHIPS FOR EACH TIME STEP        SLCU175
C     GOVERNING EQUATION (ORIGINAL FORM) IS --
C     D(THETA*C)/DT = C*D(THETA)/D(T) + THETA*D(C)/D(T)                 SLCU177
C        = -V*D(C)/D(Z)                                                 SLCU178
C                     +CKD(V)*D2(C)/D2(Z)                               SLCU179
C                                           + SOUR                      SLCU180
C                                                  - SINK               SLCU181
C     NOTE- IN THIS MODEL, VELOCITY WAS PRE-DEFINED AS (+) IN DIRECTION
C     OF DECREASING NODE NUMBER (DOWNWARD).  THUS IN EFFECT THE
C     (-) VELOCITY TERM ABOVE BECOMES (+).
C     PROCEDURE- COLLECT TERMS ASSOCIATED WITH UNKNOWN CONCENTRATIONS   SLCU182
C     FOR UPPER, MIDDLE AND LOWER NODES                                 SLCU183
C     DO FOR ALL SUBSTANCES
      MPOL=2
      DO 500 M=1,MPOL
      DO 450 N=1,NSTEPS                                                 SLCU184
      CALL GROUP                                                        SLCU185
C     SOLVE TRIDIAGONAL SCHEME, BELOW                                   SLCU186
      CALL MAT2                                                         SLCU187
  450 CONTINUE                                                          SLCU188
C     WRITE OUT RESULTS, BELOW                                          SLCU189
      CALL OUTRIT
  500 CONTINUE
      RETURN
      END                                                               SLCU192
      SUBROUTINE GROUP                                                  GRUP  1
C     GROUPS TERMS INTO COEFFICIENTS A,B,C AND D IN TRIDIAGONAL         GRUP  2
C     SCHEME.  UPPER AND LOWER NODES ARE SPECIAL CASES                  GRUP  3
      COMMON/IO    /NNODES,NSTEPS,DELT,DELZ,TSTART,TEND,FERTN(50),      SL
     1 FERTP(50),RAIN(50),EVAP(50),GWFLOW(50),SOURN(50,20),SOURP(50,20) GRUP  5
     2 ,SINKN(50,20),SINKP(50,20),VELZ(50,20),SMOIST,PSI(50,20),        GRUP  6
     3 C(2,50,20),CROP(50),THETA(50,20),VISKIN,ALPHA3,BETA3,COND(50,20),GRUP  7
     4             AC(50,20),BC(50,20),CC(50,20),DC(50,20),BFLUX(50),CFL  GRUP  8
     5,CONV,K,L,M ,CPER(50,20),CKD(50,20),CFACT1,CFACT2,N,CINIT(50)     GRUP  9
     6 ,CYEAR
      DIMENSION SOUR(50,20),SINK(50,20)
C-------------------                                                    GRUP 10
C     CIRCUMVENT CALCULATIONS FOR 1-ST TIME STEP                        GRUP 11
C     INSTEAD, INITIALIZE CONCENTRATION VALUES                          GRUP 12
      IF (N.GT.1)  GO TO 150                                            GRUP 13
      DO 300 L=1,NNODES                                                 GRUP 14
      C(M,N,L)=CINIT(L)                                                 GRUP 15
  300 CONTINUE                                                          GRUP 16
      GO TO 250                                                         GRUP 17
C     SET SOURCES AND SINK VALUES ACCORDING TO SUBSTANCE
  150 DO 350 L=1,NNODES
```

```
C     SUBSTANCE 1 IS NITRATE NITROGEN
      IF (M.EQ.1)  SOUR(N,L)=SOURN(N,L)
      IF (M.EQ.1)  SINK(N,L)=SINKN(N,L)
C     SUBSTANCE 2 IS TOTAL INORGANIC PHOSPHOROUS
      IF (M.EQ.2) SOUR(N,L)=SOURP(N,L)
      IF (M.EQ.2) SINK(N,L)=SINKP(N,L)
  350 CONTINUE
C-----------------------------                                       GRUP 18
C     START WITH BOTTOM NODE,L=1                                      GRUP 19
      L=1                                                             GRUP 20
      AC(N,L)=VELZ(N,L)/DELZ                                          GRUP 21
      BC(N,L)=((THETA(N,L)-THETA(N-1,L))/DELT)                        GRUP 22
     1      + (THETA(N,L)/DELT)  +  (VELZ(N,L)/DELZ)                  GRUP 23
      CC(N,L)=0.                                                      GRUP 24
      DC(N,L)= (THETA(N,L)*C(M,N-1,L)/DELT)                           GRUP 25
     1 +((SOUR(N,L)-SINK(N,L))*CFACT1/(CFACT2*(DELZ/2.)*THETA(N,L)))
C ---------------------------------------                             GRUP 27
C     PERFORM FOR INTERMEDIATE NODES                                  GRUP 28
      LL=NNODES-1                                                     GRUP 29
      DO 100 L=2,LL                                                   GRUP 30
      AC(N,L)=(VELZ(N,L)/(2.*DELZ))+(CKD(N,L)/(DELZ**2))              GRUP 31
      BC(N,L)=((THETA(N,L)-THETA(N-1,L))/DELT) + (THETA(N,L)/DELT)    GRUP 32
     1      + (2.*CKD(N,L)/(DELZ**2))                                 GRUP 33
      CC(N,L)=(-VELZ(N,L)/(2.*DELZ))+(CKD(N,L)/(DELZ**2))
      DC(N,L)= (THETA(N,L)*C(M,N-1,L)/DELT)                           GRUP 35
     1  +  ( (SOUR (N,L)-SINK (N,L))*CFACT1/(CFACT2*DELZ*THETA(N,L)) )
  100 CONTINUE                                                        GRUP 37
C---------------------------------------                              GRUP 38
C     PERFORM FOR TOP NODE ,L=NNODES                                  GRUP 39
      L=NNODES                                                        GRUP 40
      AC(N,L)=0.                                                      GRUP 41
      BC(N,L)= ((THETA(N,L)-THETA(N-1,L))/DELT) + (THETA(N,L)/DELT)   GRUP 42
     1      - (VELZ(N,L)/DELZ)                                        GRUP 43
      CC(N,L)= - VELZ(N,L)/DELZ                                       GRUP 44
      DC(N,L)= (THETA(N,L)*C(M,N-1,L)/DELT)                           GRUP 45
     1 +((SOUR(N,L)-SINK(N,L))*CFACT1/(CFACT2*(DELZ/2.)*THETA(N,L)))
C------------------------------------------------------------         GRUP 47
  250 RETURN                                                          GRUP 48
      END                                                             GRUP 49
      SUBROUTINE MAT2                                                 MTWO  1
C     SOLVES TRIDIAGONAL SCHEME SIMILARLY TO SUBROUTINE 'MATRIX' IN   MTWO  2
C     'INFILT' PROGRAM.                                               MTWO  3
C     ALSO COMPUTES FLUX AT BOTTOM NODE.                              MTWO  4
      COMMON/IO    /NNODES,NSTEPS,DELT,DELZ,TSTART,  ND,FERTN(50),    SL
     1 FERTP(50),RAIN(50),EVAP(50),GWFLOW(50),SOURN(50,20),SOURP(50,20) MTWO  6
     2 ,SINKN(50,20),SINKP(50,20),VELZ(50,20),SMOIST,PSI(50,20),      MTWO  7
     3 C(2,50,20),CROP(50),THETA(50,20),VISKIN,ALPHA3,BETA3,COND(50,20),MTWO  8
     4            AC(50,20),BC(50,20),CC(50,20),DC(50,20),BFLUX(50);CFL  MTWO  9
     5,CONV,K,L,M ,CPER(50,20),CKD(50,20),CFACT1,CFACT2,N,CINIT(50)   MTWO 10
     6 ,CYEAR
      COMMON/LOCMOL/LMOLE
      COMMON/CMOLE/CMOLD(2,50)
      COMMON/WTAB/JTAB(50),HTAB(50)
      COMMON/CTAB/CTABLE(2,50)
      DIMENSION  XL(50,20),RHS(50)                                    MTWO 11
C     CIRCUMVENT CALCULATIONS FOR 1-ST TIME STEP                      MTWO 12
      IF (N.EQ.1)  GO TO 580                                          MTWO 13
C     USES GAUSSIAN TECHNIQUE TO COMPUTE CONCENTRATION VALUES         MTWO 14
C     INITIALIZE LEFT HAND SIDE ARRAY (XL)                            MTWO 15
      DO550I=1,NNODES                                                 MTWO 16
      DO520J=1,NNODES                                                 MTWO 17
      XL(I,J)=0.                                                      MTWO 18
  520 CONTINUE                                                        MTWO 19
  550 CONTINUE                                                        MTWO 20
C-----------------------------                                        MTWO 21
C     INSERT VALUES INTO RIGHT HAND SIDE ARRAY (RHS)                  MTWO 22
      DO600J=1,NNODES                                                 MTWO 23
      I=J                                                             MTWO 24
      RHS(I)=DC(N,J)
  600 CONTINUE
C-----------------------------
C     INSERT VALUES OF A,B,C INTO LEFT HAND SIDE
C     ARRAY (XL)
      I=1
      JNODE=I
      XL(I,I)=BC(N,JNODE)
      XL(I,I+1)=-AC(N,JNODE)
      MM=NNODES-1
      DO660I=2,MM
      JNODE=I
      XL(I,I-1)=-CC(N, JNODE)
      XL(I,I)=BC(N,JNODE)
      XL(I,I+1)=-AC(N,JNODE)
  660 CONTINUE
      I=NNODES
      JNODE=I
      XL(I,I-1)=-CC(N,JNODE)
      XL(I,I)=BC(N,JNODE)
C     WRITE (6,1400) N
 1400 FORMAT ('1',5X,'TIME STEP=',I5)
C     DO 1500 I=1,NNODES
C     WRITE (6,2000) (XL(I,J),J=1,NNODES)
 2000 FORMAT (5X,10F6.2)
C1500 CONTINUE
      I=1
      J=1
      XDENOM=XL(1,1)
C     WRITE (6,1800) I,J,XL(I,J)
 1800 FORMAT (2I5,F6.2)
      DO750J=1,NNODES
      XL(I,J)=XL(I,J)/XDENOM
  750 CONTINUE
      RHS(I)=RHS(I)/XDENOM
      DO1000I=2,NNODES
      J=I-1
      FACTOR=-XL(I,J)/XL(J,J)
C     WRITE (6,1900) J,XL(J,J)
 1900 FORMAT (I5,F5.2)
      IPREV=I-1
      DO800J=1,NNODES
      XL(I,J)=XL(I,J)+XL(IPREV,J)*FACTOR
  800 CONTINUE
      RHS(I)=RHS(I)+RHS(IPREV)*FACTOR
      J=I
      XDENOM=XL(I,J)
C     WRITE (6,1800) I,J,XL(I,J)
      DO900J=1,NNODES
      XL(I,J)=XL(I,J)/XDENOM
  900 CONTINUE
      RHS(I)=RHS(I)/XDENOM
 1000 CONTINUE
C     DO 1700 I=1,NNODES
C     WRITE (6,2000) (XL(I,J),J=1,NNODES)
C1700 CONTINUE
C     COMPUTE CONCENTRATIONS RECURSIVELY
      L=NNODES
      JNODE=L
C     CONCENTRATION AT TOP DECREASES AS FRONT MOVES DOWNWARD
      C(M,N,JNODE)=C(M,N-1,JNODE)*(1.-((VELZ(N-1,JNODE)*DELT)/
     1   (DELZ/2.))  )*(THETA(N-1,JNODE)/THETA(N,JNODE))
      IF (C(M,N  ,JNODE).LT.0.)  C(M,N,JNODE)=0.
      LL=NNODES-1
      DO570I=1,LL
      K=NNODES-I+1
      JNODE=K
      JNODE1=JNODE-1
      C(M,N,JNODE-1)=RHS(K-1) - XL(K-1,K)*C(M,N,JNODE)
  570 CONTINUE
C----------------------------------------
C     SET CONC. AT MOLE DRAIN BELOW
      LMOLE=1
      CMOLD(M,N)=C(M,N,LMOLE)
C     SET CONC. AT WATER TABLE NODE
      JTAB(N)=1
      JJ=JTAB(N)
      CTABLE(M,N)=C(M,N,JJ)
C     COMPUTE FLUX AT BOTTOM NODE , L=1
  580 L=1
      FSAT=THETA(N,L)/SMOIST
      BFLUX(N)=VELZ(N,L)*C(M,N,L)*FSAT*CYEAR
      RETURN
      END
      SUBROUTINE OUTRIT
C     WRITES OUT INFORMATION
      COMMON/IC    /NNODES,NSTEPS,DELT,DELZ,TSTART,TEND,FERTN(50),
     1 FERTP(50),RAIN(50),EVAP(50),GWFLOW(50),SOURN(50,20),SOURP(50,20)
     2 ,SINKN(50,20),SINKP(50,20),VELZ(50,20),SMOIST,PSI(50,20),
     3 C(2,50,20),CROP(50),THETA(50,20),VISKIN,ALPHA3,BETA3,COND(50,20),
     4            AC(50,20),BC(50,20),CC(50,20),DC(50,20),BFLUX(50),CFL
     5,CONV,K,L,M ,CPER(50,20),CKD(50,20),CFACT1,CFACT2,N,CINIT(50)
     6 ,CYEAR
      WRITE (6,120)
  120 FORMAT ('1',10X,'CONCENTRATION DATA (MG/L)')
      IF (M.EQ.1)  WRITE (6,110)
      IF (M.EQ.2)  WRITE (6,115)
  110 FORMAT (20X,'SUBSTANCE IS NITRATE NITROGEN')
  115 FORMAT (20X,'SUBSTANCE IS TOTAL INORGANIC PHOSPHOROUS')
      DO 100 N=1,NSTEPS
      WRITE (6,150) N
  150 FORMAT ('        TIME STEP=',I5)
      DO 200 L=1,NNODES
      WRITE(6,250)  L,C(M,N,L)
  250 FORMAT ( ' L=',I4,'CONC=',E8.2)
  200 CONTINUE
  100 CONTINUE
C     WRITE FLUXES BELOW
      WRITE (6,350)
  350 FORMAT ('1',10X,'FLUX AT BOTTOM NODE ',/)
      WRITE (6,475)
  475 FORMAT (10X,' (LB/ACRE-YEAR)')
      DO 400 N=1,NSTEPS
      WRITE (6,450) N,BFLUX(N)
  450 FORMAT (' N=',I3,'FLUX=',E8.2)
  400 CONTINUE
      RETURN
      END
      SUBROUTINE TRAN
C     PREPARES DATA FOR TRANSFER FROM UNSATURATED ZONE MODEL
C     TO OTHER MODELS THRU DATA SETS
C------------------------------------------------------------
      COMMON/RFALL/RRAIN(50)
      COMMON/INF/RINF(50)
      COMMON/POND/CPOND(50)
      COMMON/TIME/NTIME,DTIME
      COMMON/SOIL/KSOIL
      COMMON/MOLE/CMOLD(50)
      COMMON/CMOLE/CMOLD(2,50)
      COMMON/WTAB/JTAB(50),HTAB(50)
      COMMON/CTAB/CTABLE(2,50)
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      DIMENSION FLUXN(50),FLUXP(50)
      DIMENSION CN(50),CP(50)
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C     ------------------------------------------
C     CONSICER OUTPUT TO OVERLAND FLOW MODEL
C                        --------
      WRITE (NUNOV4)NTIME,DTIME
      WRITE (6,110) NTIME,DTIME
  110 FORMAT (I5,F5.1)
C     CONVERT RRAIN FROM CM/MIN TO IN/HR
      CO 100 N=1,NTIME
      RRAIN(N)=RRAIN(N)*60./2.54
      WRITE (NUNOV4)RRAIN(N)
      WRITE (6,120) RRAIN(N)
  120 FORMAT (10X,E8.2)
  100 CONTINUE
C     CCNVERT RINF FROM CM/MIN TO CM/HR
      CU 200 N=1,NTIME
      RINF(N)=RINF(N)*60.
      WRITE (NUNOV4)RINF(N)
      WRITE (6,120) RINF(N)
  200 CCNTINUE
      WRITE (NUNOV4)(CPOND(N),N=1,NTIME)
      WRITE (6,130) (CPOND(N),N=1,NTIME)
  130 FORMAT (5X,10E8.2)
      ENC FILE NUNOV4
      REWINC NUNOV4
C     ------------------------------------------
C     CONSICER CUTPUT TO RECEIVING MODEL IN MUCK FARMS--
C                        ---------
C     FLOW AND QUALITY IN MOLE DRAINS
      IF (KSOIL.NE.2)  GO TO 300
      WRITE (NUNRE1) NTIME,DTIME
C     WRITE FLCW IN CFS PER UNIT FOOT OF MOLE LENGTH
      WRITE (NUNRE1)  (QMOLD(N),N=1,NTIME)
C     WRITE N-FLUX IN LB/DAY PER FT OF MOLE LENGTH
      M=1
      CC 400 N=1,NTIME
C     CONVERT MGD*MG/L TO LB/DAY
      FLUXN(N)=(QMOLD(N)/1.55)*(CMOLD(M,N))*8.34
      WRITE (NUNRE1) FLUXN(N)
  400 CONTINUE
C     WRITE P-FLUX IN LB/DAY PER FT OF MOLE LENGTH
      M=2
      DO 500 N=1,NTIME
      FLUXP(N)=(QMOLD(N)/1.55)*(CMOLD(M,N))*8.34
      WRITE (NUNRE1) FLUXP(N)
  500 CONTINUE
C     TO CCMPUTE FLOWS AND FLUXES FOR EACH CANAL JUNCTION,
C     MUST MULTIPLY ABOVE VALUES BY (AREA OF CATCHMENT(SQ FT) /20.)
C     SINCE SPACING OF MOLE DRAINS IS APPROXIMATELY 20 FT.
C     ----------------------
  300 CONTINUE
C     ------------------------------------------
C     CONSICER OUTPUT TO GROUNDWATER MODEL
C                        -----------
C     WATER TABLE ELEVATION AND CONCENTRATIONS--
C     TRANSFER VALUES AT LAST TIME STEP
      NN=NTIME
      CN(NN)=CTABLE(1,NN)
      CP(NN)=CTABLE(2,NN)
C     WRITE WATER TABLE HEIGHT AND NITROGEN CONC. ONLY
      WRITE (NUNGW3) HT3
      WRITE (NUNGW3) CN3
      END FILE NUNGW3
      REWINC NUNGW3
      RETURN
      END
      SUBROUTINE OVLAN1
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2;
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE OVLAN2
C     OVERLAND FLOW PROGRAM 'KWAVE'                                     KINW   1
C     --------------------                                              KINW   2
C     THIS MODEL USES KINEMATIC WAVE RELATIONSHIPS                      KINW   3
C     TO COMPUTE FLOWS FROM PLANE CATCHMENTS TO                         KINW   4
C     RECEIVING ELEMENTS.  CATCHMENTS DO NOT FEED INTO EACH OTHER.      KINW   5
C     A RECEIVING ELEMENT MAY BE CONNECTED TO MORE THAN ONE             KINW   6
C     CATCHMENT.  SCANNING PROCEDURE USED TO OBTAIN                     KINW   7
C     EQUIVALENT STORM DURATION, AVERAGING PROCEDURE                    KINW   8
C     USED TO OBTAIN EQUIVALENT MEAN (CONSTANT) RAINFALL                KINW   9
C     AND INFILTRATION RATES.  QUALITY RELATIONSHIPS ARE                KINW  10
C     INCLUDED.  PROGRAM APPLIED TO SANDY SOILS IN STUDY AREA           KINW  11
C     (APOPKA BASIN).                                                   KINW  12
C...........................................................            KINW  13
C...........................................................            KINW  14
C                PARTIAL LIST OF VARIABLES-                             KINW  15
C     NREC=NO. OF RECEIVING ELEMENTS (TOTAL)                            KINW  16
C     NDEP=NO. OF RECEIVING ELEMENTS CONSTITUTING 'SMALL'               KINW  17
C                SURFACE DEPRESSIONS (TYPE1)                            KINW  18
C     NBODY= NO. OF RECEIVING ELEMENTS LOCATED ON                       KINW  19
C                'LARGE' BODY OF WATER (TYPE2)                          KINW  20
C     NCATCH(I)=NO. OF CATCHMENTS FEEDING TO I-TH                       KINW  21
C                RECEIVING ELEMENT                                      KINW  22
C     NTYPE(I)=TYPE OF I-TH RECEIVING ELEMENT (1 OR 2 ABOVE)            KINW  23
C     X(I)=X-COORDINATE OF I-TH RECEIVING ELEMENT                       KINW  24
C     Y(I)=Y-COORDINATE OF I-TH RECEIVING ELEMENT                       KINW  25
C     NTC=TOTAL NO. OF CATCHMENTS                                       KINW  26
C     XLM(K,M)=LENGTH THROUGH M-TH INTERVAL IN K-TH CATCHMENT           KINW  27
C                IN FEET                                                KINW  28
C     XLENG(K)=LENGTH OF K-TH CATCHMENT (IN THE HORIZONTAL)             KINW  29
C                IN FEET                                                KINW  30
C     WIDTH(K)=WIDTH OF K-TH CATCHMENT                                  KINW  31
C                IN FEET                                                KINW  32
C     SLOPE(K)=SLOPE OF K-TH CATCHMENT                                  KINW  33
C                IN (FT/FT)                                             KINW  34
C     ALPHA(K)=ALPHA FACTOR OF K-TH CATCHMENT (SEE EAGLESON)            KINW  35
C                (DIMENSIONLESS)                                        KINW  36
C     EN(K)=MANNING 'N' ROUGHNESS COEF FOR K-TH CATCHMENT               KINW  37
C     EM(K)=M-FACTOR OF K-TH CATCHMENT (SEE EAGLESON)                   KINW  38
C                (HERE, EM(K)=2.)                                       KINW  39
C     NLINK(K)= NO. OF RECEIVING ELEMENT TO WHICH K-TH CATCHMENT        KINW  40
C                 IS LINKED                                             KINW  41
C     MINT=NO. OF INTERVALS INTO WHICH EVERY CATCHMENT IS DIVIDED       KINW  42
C     NT=NO. OF TIME STEPS IN PERIOD                                    KINW  43
C     DT=TIME INCREMENT  IN MINUTES                                     KINW  44
C     XRAIN(L)=RAINFALL RATE AT L-TH TIME STEP                          KINW  45
C                IN (INCHES/HOUR)                                       KINW  46
C     XINF(L)INFILTRATION RATE AT L-TH TIME STEP (FLOW BETWEEN UPPER    KINW  47
C                TWO NODES IN UNSATURATED MODEL) IN (CM/HOUR)           KINW  48
C     XPOND(L)=PONDING DEPTH AT L-TH TIME STEP (FROM UNSATURATED        KINW  49
C                MODEL), IN CM                                          KINW  50
C     LSTOP=TIME STEP AT WHICH PONDING DEPTH BECOMES ZERO               KINW  51
C     XF=AVERAGE INFILTRATION RATE FOR 1 L LSTOP                        KINW  52
C                IN (FT/MIN)
C     NTR=NO. OF TIME STEP AT WHICH MAXIMUM PONDING DEPTH OCCURS        KINW  54
C     TR=TIME CORRESPONDING TO 'NTR' ABOVE,ASSUMED TO BE EQUIVALENT     KINW  55
C                STORM DURATION, IN MIN                                 KINW  56
C     XI=AVERAGE RAINFALL RATE FOR 1 L LSTOP                            KINW  57
C                IN (FT/MIN)                                            KINW  58
C     YLENG(K)=ELEVATION DIFFERENCE BETWEEN UPPER ANDLOWER PORTIONS     KINW  59
C                OF K-TH CATCHMENT, IN FT                               KINW  60
C     SL(K)='TRUE' LENGTH OF K-TH CATCHMENT                             KINW  61
C                IN FEET                                                KINW  62
C     SLM(K,M)=TRUE LENGTH,AS ABOVE,THRU M-TH INTERVAL                  KINW  63
C                IN FEET                                                KINW  64
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C       SINTH(K)=SINE OF ANGLE THETA WITH HORIZONTAL FOR K-TH CATCHMENT
C       TC(K,M)=TIME OF CONCENTRATION IN K-TH CATCHMENT                   KINW 65
C                 AT M-TH POINT, IN MIN                                   KINW 66
C       VEL(K,L,M)=OUTFLOW VELOCITY IN K-TH CATCHMENT AT OUTLET           KINW 67
C                 AT L-TH TIME STEP AND AT M-TH POINT, IN FT/MIN          KINW 68
C       YL(K,L,M)=DEPTH IN K-TH CATCHMENT AT L-TH TIME STEP,AT M-TH POINT KINW 69
C                 IN INCHES                                               KINW 70
C       QUNIT(K,L,M)=UNIT OUTFLOW,K-TH CATCHMENT AT L-TH TIME STEP,       KINW 71
C                 AT M-TH POINT, IN (CUBIC FEET PER MIN/FT)               KINW 72
C       QTOT(K,L,M)=OUTFLOW AT K-TH CATCHMENT AT L-TH TIME STEP,          KINW 73
C                 AT M-TH POINT, IN (CUBIC FT / SEC)                      KINW 74
C       QRCV(I,L)=INFLOW INTO I-TH RECEIVING ELEMENT AT L-TH TIME STEP    KINW 75
C                 IN (CUBIC FEET/SEC)                                     KINW 76
C       TI(K,M)=TIME AT WHICH YL VANISHES IN K-TH CATCHMENT,AT M-TH POINT KINW 77
C                 IN MIN                                                  KINW 78
C       TP(K,M)=TIME AT WHICH YL BEGINS TO DECREASE AFTER ACHIEVING       KINW 79
C                 PEAK DEPTH, AT M-TH POINT, IN MIN                       KINW 80
C       VBAR(K,L)=AVERAGE VELOCITY AT K-TH CATCHMENT AT L-TH TIME STEP    KINW 81
C                 IN FT/SEC                                               KINW 82
C       YBAR(K,L)=AVERAGE DEPTH AT K-TH CATCHMENT AT L-TH TIME STEP,IN FT KINW 83
C       PMS(K,L)=RATE OF INPUT (SUSPENSION) OF SOLIDS INTO WATER          KINW 84
C                 IN LB/ACRE/SEC                                          KINW 85
C       PMD(K,L)=RATE OF INPUT OF DISSOLVED SUBSTANCES INTO WATER         KINW 86
C                 IN LB/ACRE/SEC                                          KINW 87
C       R=HYDRAULIC RADIUS, IN FT                                         KINW 88
C       VCRIT=AVERAGE VELOCITY AT WHICH PARTICLES OF DIAMETER 'D'         KINW 89
C                 WILL BE TRANSPORTED, IN FT/SEC                          KINW 90
C       CK=SHIELD'S CONSTANT=0.056                                        KINW 91
C       SS=SPECIFIC GRAVITY OF PARTICLE (APPROX.=2.)                      KINW 92
C       D=DIAMETER OF PARTICLE (ASSUMED TO BE D50) ,IN FT                 KINW 93
C       PSMAX=MAXIMUM SCOURING RATE IN LB/ACRE/SEC                        KINW 94
C       CPOL(K,L)=FLUX OF SUSPENDED POLLUTANT (PHOSPHOROUS IN THIS CASE)  KINW 95
C          IN OUTLET FLOW (LB/DAY)
C       RO=DENSITY OF WATER
C       PZERO=INITLAL RATE OF UPTAKE OF DISSOLVED SUBSTANCE (NITRATE-N    KINW 98
C          IN THIS CASE) IN (LB/ACRE/SEC)
C       CDECAY=DECAY CONSTANT FOR 'PZERO' ABOVE, IN (1/MIN)
C       CDIS(K,L)=FLUX OF DISSOLVED SUBSTANCE (NITRATE-N IN THIS CASE)    KINW101
C          AT OUTLET IN (LB/DAY)
C       CPSI=DUBOYS' PSI-FUNCTION FOR A GIVEN SOIL PARTICLE SIZE
C       TAUC=DUBOYS' CRITICAL SHEAR STRESS FOR A GIVEN PARTICLE SIZE
C       PFRAC=FRACTION OF TOTAL INORGANIC PHOSPHOROUS IN SOIL (LB/LB)
C       GAMMA=UNIT WEIGHT OF WATER (LB/CU FT)
C       CPHOS=FLUX OF TOTAL INORGANIC PHOSPHOROUS INTO
C             RECEIVING ELEMENT (LB/DAY)
C       CNIT=FLUX OF NITRATE - N INTO RECEIVING ELEMENT (LB/DAY)
C       KC(K)ORIGINAL CODE NO. (FROM PROJECT MAP) OF K-TH CATCHMENT
C             READ IN.
C..........................................................................
C       DEFINE DATA STORAGE BLOCKS,BELOW                                  KINW104
        COMMON/IO  / NREC,NDEP,NBODY,NCATCH(70),KC(200)                   KINW105
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                     QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RO,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2;
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
C..........................................................................
C       READ INPUT DATA BELOW                                             KINW116
C       ---------------------                                             KINW117
C       READ PHYSICAL DATA AND LINKAGE DATA BETWEEN RECEIVING ELEMENTS    KINW118
C       AND CATCHMENTS                                                    KINW119
                                                                          KINW120
      READ (5,100)  NREC,NDEP,NBODY,MINT,NTC                            KINW121
  100 FORMAT (5I5)                                                      KINW122
C     DO 125 I=1,NREC                                                   KINW123
C     READ (5,120) II,NTYPE(I),NCATCH(I),X(I),Y(I)                      KINW124
C 120 FORMAT (I3,I2,I2,4X,2F5.2)                                        KINW125
C 125 CONTINUE                                                          KINW126
C     READ (5,110) (NCATCH(I),I=1,NREC)                                 KINW127
C 110 FORMAT (25I2)                                                     KINW128
      DO 130 K=1,NTC                                                    KINW129
      READ (5,135) KK,NLINK(K),XLENG(K),WIDTH(K),SLOPE(K)               KINW130
     1 ,EN(K),EM(K)                                                     KINW131
  135 FORMAT (I4,3X,I3,2F5.0,F5.4,F5.3,F5.2)                            KINW132
C     SET VALUES OF EM(K) FOR TURBULENT FLOW
      EM(K)=5./3.
      KC(K)=KK
  130 CONTINUE                                                          KINW133
C     READ HYDROLOGIC DATA                                              KINW134
      READ (5,140) NT,DT
  140 FORMAT (I5,F5.2)                                                  KINW136
C     FOR THE PRESENT, ASSUME DATA BELOW HOLDS FOR EVERY CATCHMENT      KINW137
      DO 160 L=1,NT                                                     KINW138
      READ (5,150)  XRAIN(L),XINF(L),XPOND(L)                           KINW139
      FACTOR=1.3
C     ADJUST RAINFALL INTENSITY FOR VARIOUS RUNS
      XRAIN(L)=XRAIN(L)*FACTOR
C     UNITS FOR 'XRAIN'=IN/HR , FOR 'XINF'=CM/HR , FOR 'XPOND'=CM       KINW140
C     NOTE-- VARIABLES ABOVE COULD BE OBTAINED THROUGH INTERFACING      KINW141
C                 INSTEAD OF READING IN                                 KINW142
  150 FORMAT (3F10.2)                                                   KINW143
  160 CONTINUE                                                          KINW144
C     READ (NUNOV4)NT,DT
      DO 350 L=1,NT
C     READ (NUNOV4) XRAIN(L)
  350 CONTINUE
      WRITE (6,210) (XRAIN(L),L=1,NT)
      DO 450 L=1,NT
C     READ (NUNOV4) XINF(L)
  450 CONTINUE
      WRITE (6,210) (XINF(L),L=1,NT)
C     READ (NUNOV4)(XPOND(L),L=1,NT)
      WRITE (6,210) (XPOND(L),L=1,NT)
  210 FORMAT (5X,12E8.2)
C     REWIND NUNOV4
      READ (5,170) CK,SS,D                                              KINW145
  170 FORMAT (2F5.1,F7.5)
      READ (5,180) PSMAX,PZERO,CDECAY                                   KINW147
  180 FORMAT (3F5.1)                                                    KINW148
      CALL AVE                                                          KINW149
      CALL WAVE                                                         KINW150
      CALL RECV                                                         KINW151
      CALL RQUAL                                                        KINW152
      CALL WRIT                                                         KINW153
      RETURN
C     DEBUG SUBCHK,TRACE,INIT,SUBTRACE                                  KINW155
      END                                                               KINW156
      SUBROUTINE AVE                                                      AVE  1
C     PERFORMS AVERAGING COMPUTATIONS INVOLVING                           AVE  2
C     RAINFALL AND INFILTRATION.  PREPARES DATA FOR USE IN                AVE  3
C     KINEMATIC WAVE CALCULATIONS.                                        AVE  4
      COMMON/ID  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                  QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
C      SCAN TIME HORIZON TO FIND TIME STEP AT WHICH                     AVE 15
C      PONDING DEPTH BECOMES 'PERMANENTLY' ZERO.  WORK                  AVE 16
C      BACKWARD IN TIME.                                                AVE 17
       DO 200 L=1,NT                                                    AVE 18
       NDUMMY=NT+1-L                                                    AVE 19
       IF (XPOND(NDUMMY).GT.0.)  GO TO 250                              AVE 20
  200  CONTINUE                                                         AVE 21
  250  LSTOP=L                                                          AVE 22
C      COMPUTE AVERAGE INFILTRATION RATE FOR PERIOD                     AVE 23
C      ENDING AT TIME STEP L=LSTOP                                      AVE 24
       SUM=0.                                                           AVE 25
       DO 300 L=1,LSTOP                                                 AVE 26
       SUM=SUM+XINF(L)                                                  AVE 27
  300  CONTINUE                                                         AVE 28
       DENOM=LSTOP-1                                                    AVE 29
C      CONVERT 'XF' FROM CM/HR  TO FT/MIN USING 'C1'                    AVE 30
       C1=0.0328/60.                                                    AVE 31
       XF=(SUM/DENOM)*C1                                                AVE 32
C      COMPUTE TOTAL RAINFALL FOR SAME TIME PERIOD                      AVE 33
C      AS ABOVE                                                         AVE 34
       SUM=0.                                                           AVE 35
       DO 350 L=1,LSTOP                                                 AVE 36
       SUM=SUM+XRAIN(L)*DT                                              AVE 37
  350  CONTINUE                                                         AVE 38
       TRAIN=SUM                                                        AVE 39
C      ASSIGN A DURATION TIME TO RAINSTORM.  SET DURATION               AVE 40
C      TIME EQUAL TO TIME AT WHICH MAXIMUM DEPTH OCCURRED.  SCAN        AVE 41
C      DATA ON PONDING DEPTH.                                           AVE 42
       INDX=1                                                           AVE 43
       STOR=0.                                                          AVE 44
       DO 400 L=1,LSTOP                                                 AVE 45
       IF (XPOND(L).GE.STOR)  INDX=L                                    AVE 46
       XARG=XPOND(L)                                                    AVE 47
       STOR = AMAX1(STOR,XARG)                                          AVE 48
  400  CONTINUE                                                         AVE 49
       NTR=INDX                                                         AVE 50
       TR=NTR*DT                                                       AVE 50A
C      DETERMINE AVERAGE RAINFALL RATE FOR O T TR                       AVE 51
       AVRAIN=TRAIN/(NTR*DT)                                            AVE 52
C      CONVERT 'XI' FROM IN/HR  TO FT/MIN USING 'C2'                    AVE 53
       C2=0.0833/60.                                                    AVE 54
       XI=AVRAIN*C2                                                     AVE 55
       RETURN                                                           AVE 56
C      DEBUG SUBCHK,TRACE,INIT,SUBTRACE
       END                                                              AVE 57
       SUBROUTINE WAVE                                                 WAVE  1
C      CARRIES OUT KINEMATIC WAVE COMPUTATIONS                         WAVE  2
C      WITH VALUES OF XI,XF,TR AND OTHER PHYSICAL                      WAVE  3
C      VARIABLES.  ULTIMATELY IT COMPUTES DISCHARGES                   WAVE  4
C      AT LOWER END OF EACH CATCHMENT                                  WAVE  5
C      PERFORM COMPUTATIONS WITH PHYSICAL VARIABLES                    WAVE  6
       COMMON/IC  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                 QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPCL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
       DO 200 K=1,NTC                                                  WAVE 17
       YLENG(K)=XLENG(K)*SLOPE(K)                                      WAVE 18
       RSQ=XLENG(K)**2 + YLENG(K)**2                                   WAVE 19
       SL(K)=RSQ**0.5                                                  WAVE 20
       SINTH (K)=YLENG(K)/SL(K)                                        WAVE 21
       ALPHA(K)=1.49*(SINTH(K)**0.5)/EN(K)                             WAVE 22
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C     TURBULENT FLOW ASSUMED ABOVE                                      WAVE 23
  200 CONTINUE                                                          WAVE 24
C---------------------------------------------------------------------  WAVE 25
C     PERFORM THE FOLLOWING CALCULATIONS FOR EVERY INTERVAL             WAVE 26
      DO 700 M=1,MINT                                                   WAVE 27
C     COMPUTE TIME OF CONCENTRATION BELOW                               WAVE 28
      DO 300 K=1,NTC                                                    WAVE 30
      SLM(K,M)=SL(K)*(M/FLOAT(MINT))                                    WAVE 30A
      XNUM=SLM(K,M)* ((XI-XF)**(1.-EM(K)))                              WAVE 31
C     CONVERSION BELOW--60 SEC/MIN
      XDEN=ALPHA(K) *60.                                                WAVE 32
      EMINV=1.0/EM(K)                                                   WAVE 33
      TC(K,M)= (XNUM/XDEN) **EMINV                                      WAVE 34
  300 CONTINUE                                                          WAVE 35
      WRITE (6,350) TR
  350 FORMAT ('1','  STORM DURATION=',F7.2,'MIN')
      M=1
      DO 360 K=1,NTC
      WRITE (6,370) K,TC(K,M)
  370 FORMAT (' CATCH NO=',I5,'TIME OF CONC=',F7.2,'MIN')
  360 CONTINUE
C     FOR EACH CATCHMENT COMPUTE DEPTH AT OUTLET                        WAVE 36
C     DEPENDING ON RELATIVE VALUES OF TR AND TC(K).                     WAVE 37
C     CASE 1 TR TC(K,M)  SUBROUTINE HIDUR                               WAVE 38
C     CASE 2 TR TC(K,M)  SUBROUTINE LODUR                               WAVE 39
      DO 400 K=1,NTC                                                    WAVE 40
      IF (TR.GE.TC(K,M)) CALL HIDUR                                     WAVE 41
      IF (TR.LT.TC(K,M))  CALL LODUR                                    WAVE 42
  400 CONTINUE                                                          WAVE 43
C     COMPUTE VELOCITIES AND FLOWS USING DEPTHS                         WAVE 44
      DO 500 K=1,NTC                                                    WAVE 45
      DO 600 L=1,NT                                                     WAVE 46
C     'VEL' BELOW IN FT/SEC
C     (COMPATIBLE WITH MANNING'S N IN ALPHA COMPUTATION)
C     PREVENT BASE ZERO IN OPERATION BELOW
      IF (YL(K,L,M).LE.0.)  YL(K,L,M)=0.1E-15
      VEL(K,L,M)=ALPHA(K) * (YL(K,L,M)**(EM(K)-1.))                     WAVE 47
C     CONVERT TO (FT/MIN)
      VEL(K,L,M)=VEL(K,L,M)*60.
C     'QUNIT' BELOW IN (CU FT PER MIN/FT)                               WAVE 48
      QUNIT        =VEL(K,L,M) * YL(K,L,M)
C     'QTOT' BELOW IN (CU FT/SEC)                                       WAVE 50
      C3=0.0167                                                         WAVE 51
      QTOT(K,L,M)=QUNIT          * WIDTH(K)*C3
  600 CONTINUE                                                          WAVE 53
  500 CONTINUE                                                          WAVE 54
  700 CONTINUE                                                          WAVE 55
      RETURN                                                            WAVE 56
C     DEBUG SUBCHK,TRACE,INIT,SUBTRACE
      END                                                               WAVE 57
      SUBROUTINE RECV                                                   RECV  1
C     COMPUTES TOTAL FLOW INTO EACH RECEIVING ELEMENT                   RECV  2
C     FROM EACH CATCHMENT,FOR EACH TIME STEP                            RECV  3
      COMMON/IO  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                 QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPCL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
C     WORK ONLY WITH LAST INTERVAL OF EACH CATCHMENT                    RECV 14
      M=MINT                                                            RECV 15
C     INITIALIZE ARRAY BELOW TO ZERO                                    RECV 16
      DO 200 L=1,NT                                                     RECV 17
      DO 300 I=1,NREC                                                   RECV 18
      QRCV(I,L)=0.                                                      RECV 19
  300 CONTINUE                                                          RECV 20
  200 CONTINUE                                                          RECV 21
      DO 400 L=1,NT                                                     RECV 22
      DO 500 K=1,NTC                                                    RECV 23
      INDEX=NLINK(K)                                                    RECV 24
C     'QRCV' BELOW IN (CU FT/SEC)                                       RECV 25
      QRCV(INDEX,L)=QRCV(INDEX,L) + QTOT(K,L,M)                         RECV 26
  500 CONTINUE                                                          RECV 27
  400 CONTINUE                                                          RECV 28
      RETURN                                                            RECV 29
      END                                                               RECV 30
      SUBROUTINE HIDUR                                                  HIDV  1
C     UTILIZES KINEMATIC WAVE RELATIONSHIPS FOR THE CASE                HIDV  2
C     TR TC(K,M)    (HIGH DURATION)                                     HIDV  3
      COMMON/ID  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                  QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
C     DETERMINE TI(K,M),TIME AT WHICH YL(K,L,M) VANISHES                HIDV 14
      TI(K,M)=TR + (TC(K,M)* (XI-XF)/((XI*XF)**0.5))                    HIDV 15
C     COMPUTE DEPTH AT OUTLET AT DIFFERENT TIMES                        HIDV 16
      DO 200 L=1,NT                                                     HIDV 17
      T=L*DT                                                            HIDV 18
  210 IF (T.GT.TC(K,M))  GO TO 220                                      HIDV 19
      YL(K,L,M)= (XI-XF)*T                                              HIDV 20
      GO TO 200                                                         HIDV 21
  220 IF (T.GT.TR)  GO TO 230                                           HIDV 22
      YL(K,L,M)= (XI-XF) * TC(K,M)                                      HIDV 23
      GO TO 200                                                         HIDV 24
  230 IF (T.GT.TI(K,M))  GO TO 240                                      HIDV 25
      TERM1=(XI-XF)**0.5                                                HIDV 26
      TERM2= (XI*((T-TR)**2) + (TC(K,M)**2) * (XI-XF))**0.5             HIDV 27
      TERM3=XI*(T-TR)                                                   HIDV 28
      YL(K,L,M)=TERM1*TERM2-TERM3                                       HIDV 29
      GO TO 200                                                         HIDV 30
  240 YL(K,L,M)=0.                                                      HIDV 31
  200 CONTINUE                                                          HIDV 32
      RETURN                                                            HIDV 33
      END                                                               HIDV 34
      SUBROUTINE LODUR                                                  LODV  1
C     UTILIZES KINEMATIC WAVE RELATIONSHIPS FOR THE                     LODV  2
C     CASE TR TC(K,M)                 (LOW DURATION)                    LODV  3
      COMMON/ID  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                  QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
C     3 MAIN CASES ARISE-- 1.TI(K,M) TP(K,M) , 2.TI(K,M)=TP(K,M)        LODV 14
C                              3.TI(K,M) TP(K,M)                        LODV 15
C     COMPUTE VALUES OF TI,TP TO MAKE COMPARISONS                       LODV 16
      TI(K,M)=TR + TC(K,M)*(XI-XF)/((XF*XI)**0.5)                       LODV 17
      YLR=XI*TR                                                         LODV 18
      TCSTAR=SLM(K,M)/(ALPHA(K)*(YLR**(EM(K)-1.)))                      LODV 19
      TP(K,M)=TR + (TCSTAR-TR)/EM(K)                                    LODV 20
      TINDEX=TP(K,M)-TI(K,M)                                            LODV 21
      IF (TINDEX)  100,200,300                                          LODV 22
```

```
C-------------------------------------------------------
C     CASE 1 BELOW
C     COMPUTE DEPTH AT DIFFERENT TIMES
  100 DO 150 L=1,NT
      T=L*DT
  110 IF (T.GT.TR)  GO TO 120
      YL(K,L,M)=(XI-XF)*T
      GO TO 150
  120 IF (T.GT.TP(K,M))  GO TO 130
      YL(K,L,M)=XI*TR-XF*T
      GO TO 150
  130 IF (T.GT.TI(K,M))  GO TO 140
      TERM1=(XI-XF)**0.5
      TERM2=(XI*((T-TR)**2)+(TC(K,M)**2) * (XI-XF))**0.5
      TERM3=XI*(T-TR)
      YL(K,L,M)=TERM1*TERM2-TERM3
      GO TO 150
  140 YL(K,L,M)=0.
  150 CONTINUE
      RETURN
C-------------------------------------------------------
C     CASE 2 BELOW
C     COMPUTE DEPTH AT DIFFERENT TIMES
  200 DO 250 L=1,NT
      T=L*DT
  210 IF (T.GT.TR)  GO TO 220
      YL(K,L,M)=(XI-XF)*T
      GO TO 250
  220 IF(T.GT.TP(K,M))  GO TO 230
      YL(K,L,M)=XI*TR-XF*T
      GO TO 250
  230 YL(K,L,M)=0.
  250 CONTINUE
      RETURN
C-------------------------------------------------------
C     CASE 3 BELOW
C     COMPUTE DEPTH AT DIFFERENT TIMES
  300 DO 350 L=1,NT
      T=L*DT
  310 IF (T.GT.TR)  GO TO 320
      YL(K,L,M)=(XI-XF)*T
      GO TO 350
  320 IF (T.GT.TI(K,M))  GO TO 330
      YL(K,L,M)=XI*TR-XF*T
      GO TO 350
  330 YL(K,L,M)=0.
  350 CONTINUE
      RETURN
      END
      SUBROUTINE RQUAL
C     PERFORMS WATER QUALITY COMPUTATIONS AT THE VARIOUS
C     SUBCATCHMENTS.  RELATES THESE TO INFLOWS INTO
C     RECEIVING ELEMENTS.
      COMMON/IC  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                 QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RO,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
      COMMON/NUM3/QPHOS(200,20) ,QNIT(200,20)
C-------------------------------------------------------
C     AT EACH TIME STEP, COMPUTE MEAN VELOCITY FOR EACH
C     CATCHMENT BASED ON VELOCITIES AT ITS INTERVAL POINTS.
      DO 100 L=1,NT
      DO 200 K=1,NTC                                                    RQUA 19
      SUM1=0.                                                           RQUA 20
      SUM2=0.                                                           RQUA 21
      DO 300 M=1,MINT                                                   RQUA 22
      SUM1=SUM1+VEL(K,L,M)                                              RQUA 23
      SUM2=SUM2+YL(K,L,M)                                               RQUA 24
  300 CONTINUE                                                          RQUA 25
      C4=0.0167                                                         RQUA 27
C     'VBAR' BELOW IN FT/MIN
      VBAR(K,L)=(SUM1/MINT)
C     'YBAR' BELOW IN FT                                                RQUA 29
      YBAR(K,L)=SUM2/MINT                                               RQUA 30
  200 CONTINUE                                                          RQUA 31
  100 CONTINUE                                                          RQUA 32
C-----------------------------------------------------------            RQUA 33
C     COMPUTE VALUES OF PMS(K,L) AND PMD(K,L) FOR EACH TIME STEP.       RQUA 34
C     DETERMINE FIRST SCOURING OF SOLIDS--PMS(K,L)                      RQUA 35
C                                ......                                 RQUA 36
      DO 400 L=1,NT                                                     RQUA 37
      DO 450 K=1,NTC                                                    RQUA 38
      R=YBAR(K,L)                                                       RQUA 39
C     FOR 'VCRIT' FORMULA SEE PP. 219,346-347 OF 'STORM WATER           RQUA 40
C     MANAGEMENT MODEL',VOL.1                                           RQUA 41
C     'VCRIT' SHOULD BE IN (FT/SEC)                                     RQUA 42
      VCRIT=(1.486/EN(K)) * (R**0.167) * ((CK*(SS-1.)*D)**0.5)          RQUA 43
C     COMPUTE CONCENTRATION IN FLOW TO RECEIVING ELEMENTS               RQUA 44
C     CONCENTRATION AT OUTFLOW AT L-TH TIME STEP DEPENDS                RQUA 45
C     ON EROSION RATES PRIOR TO THAT TIME.  LOCATE TIME STEP            RQUA 46
C     THAT LIES AT APPROXIMATE MIDPOINT (IN TIME) OF THESE CONDITIONS.  RQUA 47
C     ---------------------------------------------------
C     INSTEAD OF USING SHIELD'S FORMULA, WHICH APPLIES MORE TO
C     FINITE AMOUNTS OF SEDIMENTS, USE THE DU BOYS BEDLOAD FORMULA
C     (CHOW,P.17-52) , APPLIED AT CATCHMENT OUTLET
C     FOLLOWING DATA FOR FINE SANDS, SUCH AS THOSE IN STUDY AREA
      CPSI=523000.
      TAUC=0.0162
      GAMMA=62.4
      PFRAC=0.00327
      T=L*DT                                                            RQUA 48
      M=MINT                                                            RQUA 49
C     BYPASS OPERATIONS FOR NEAR-ZERO VELOCITIES
      IF (VBAR(K,L).LT.0.1E-5) LLAG=0
      IF (VBAR(K,L).LT.0.1E-5) GO TO 470
      TLAG=  ((XLENG(K)/2.)/VBAR(K,L))                                  RQUA 50
      LLAG=TLAG/DT                                                      RQUA 51
  470 LADJ=L-LLAG                                                       RQUA 52
      IF (LADJ.LT.1)  LADJ=1                                            RQUA 53
C     IF DESIRED TO ADJUST FOR PREVIOUS SCOURING HISTORY,
C     COULD REPLACE YBAR(K,LADJ) FOR YL(K,L,M) BELOW
      QS=CPSI*YBAR(K,LADJ)*SLOPE(K)*( (YL(K,L,M)   *SLOPE(K))
     1       - (TAUC/GAMMA) )
      IF (QS.LT.0.)  QS=0.
C     CONVERT FROM (LB/SEC) TO (LB/DAY)
      QS=QS*86400.
      CPOL(K,L)=QS*PFRAC
C     CPOL IS IN (LB OF POLLUTANT/DAY)
C     IF OUTFLOW RATE IS ZERO AT CURRENT TIME STEP SET CPOL=0.
      IF (QTOT(K,L,M).EQ.0.)  CPOL(K,L)=0.
  450 CONTINUE                                                          RQUA 61
  400 CONTINUE                                                          RQUA 62
C-----------------------------------------------------------            RQUA 63
C     DETERMINE UPTAKE OF DISSOLVED SUBSTANCES                          RQUA 64
      DO 500 L=1,NT                                                     RQUA 65
      DO 550 K=1,NTC                                                    RQUA 66
      T=L*DT                                                            RQUA 67
C     BYPASS OPERATIONS FOR NEAR-ZERO VELOCITIES
      IF (VBAR(K,L).LT.0.1E-5) TADJ=0.
      IF (VBAR(K,L).LT.0.1E-5) GO TO 570
      TADJ=T- ((XLENG(K)/2.)/VBAR(K,L))                                 RQUA 68
  570 IF (TADJ.LT.O.)  TADJ=0.                                          RQUA 69
C     CONSIDER 1-ST ORDER DECAY BELOW                                   RQUA 70
      AR=-CDECAY*TADJ                                                   RQUA 71
C     PZERO ASSUMED TO BE ZERO FOR NITRATE, TEMPORARILY
      PZERO=0.
      PMD(K,L)=PZERO*EXP(AR)                                            RQUA 72
      M=MINT                                                            RQUA 74
      DSFLUX=PMD(K,L)*XLENG(K)*WIDTH(K)/43560.                          RQUA 75
C     DSFLUX UNITS IN (LB/SEC)
      CDIS(K,L)=DSFLUX*86400.
C     IF OUTFLOW RATE IS ZERO , SET CDIS=0.
      IF (QTOT(K,L,M).EQ.0.)  CDIS(K,L)=0.                              RQUA 75B
  550 CONTINUE                                                          RQUA 77
  500 CONTINUE                                                          RQUA 78
C-----------------------------------------------                        RQUA 79
C     NOTE--COULD CONVERT ABOVE CONCENTRATIONS INTO WEIGHTS,            RQUA 80
C     IF NECESSARY                                                      RQUA 81
C     INITIALIZE ARRAYS
      DO 700 II=1,NREC
      DO 750 L=1,NT
      CPHOS (II,L)=0.
      CNIT(II,L)=0.
  750 CONTINUE
  700 CONTINUE
C     OBTAIN TOTAL FLUXES INTO EACH RECEIVING ELEMENT
      DO 800 L=1,NT
      DO 900 K=1,NTC
      INDX=NLINK(K)
      CPHOS(INDX,L)=CPHOS(INDX,L) + CPOL(K,L)
      CNIT(INDX,L)=CNIT(INDX,L) + CDIS(K,L)
  900 CONTINUE
  800 CONTINUE
      RETURN                                                            RQUA 82
C     DEBUG SUBCHK,TRACE,INIT,SUBTRACE
      END                                                               RQUA 83
      SUBROUTINE WRIT                                                   WRIT  1
C     WRITES OUT PERTINENT INFORMATION                                  WRIT  2
      COMMON/ID  / NREC,NDEP,NBODY,NCATCH(70),KC(200)
     1,NTYPE(2),NTC,XLENG(200),WIDTH(200),SLOPE(200),
     2 ALPHA(200),EN(200),EM(200),NLINK(200),NT,DT,XRAIN(200),
     3 XINF(20),XPOND(20),LSTOP,XF,NTR,TR,XI,
     4 YLENG(200),SL(200),SINTH(200),TC(200,1),
     5 QRCV(200,20),TI(200,20),TP(200,1),XLM(200,1),MINT,SLM(200,1),
     6 YL(200,20,1),VEL(200,20,1),                    QTOT(200,20,1),
     7VBAR(200,20),YBAR(200,20),PMS(200,20),PMD(200,20),CK,SS,D,PSMAX,
     8 CPOL(200,20),RC,PZERO,CDECAY,CDIS(200,20)
     9 ,X(200),Y(200),I,K,L,M
      COMMON/NUM3/CPHOS(200,20) ,CNIT(200,20)
      M=MINT                                                            WRIT 13
      WRITE (6,300)                                                     WRIT 14
  300 FORMAT (' STEP  CAT  FLOW    P LOAD    NO3-N LOAD')
      WRITE (6,350)
  350 FORMAT ('              (CFS)   (LB/DAY)  (LB/DAY)  ')
      DO 100 K=1,NTC
      DO 200 L=1,NT
      WRITE (6,250) L,K,QTOT(K,L,M),CPOL (K,L),CDIS(K,L)                WRIT 18
  250 FORMAT (2I5,3F10.2)                                               WRIT 19
  200 CONTINUE                                                          WRIT 20
  100 CONTINUE                                                          WRIT 21
      RETURN                                                            WRIT 22
      END
      SUBROUTINE OVLAN3
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE OVLAN4
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE REC1
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE REC2
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE REC3
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      RETURN
      END
      SUBROUTINE GWBLCK
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      CALL PHI
      CALL GWQUAL
      RETURN
      END
      SUBROUTINE PHI
C     GROUNDWATER (SATURATED ZONE) FLOW PROGRAM.                        PHI   1
C     TWO-DIMENSIONAL STEADY-STATE.                                     PHI   2
C     PROGRAM USES NUMERICAL TECHNIQUES ITERATIVELY TO                  PHI   3
C     COMPUTE HEAD (PHI) AT ALL POINTS IN A GRID SYSTEM, GIVEN          PHI   4
C     SOME BOUNDARY CONDITIONS.                                         PHI   5
C     THEN DETERMINES VELOCITY AND ANGLE AT EACH POINT.                 PHI   6
C.......................................................
C     PARTIAL LIST OF VARIABLES--
C     J=SUBSCRIPT FOR ROW NO.
C     NROW = NO. OF ROWS IN GRID
C     I = SUBSCRIPT FOR COLUMN NO.
C     NCOL = NO. OF COLUMNS IN GRID
C     NCLASS = NODE CLASS MATRIX FOR FLOW EQUATIONS
C     GROUND = GROUND ELEVATION IN FT.
C     WTABLE = WATER TABLE ELEVATION , IN FT.
C     BOTOM = ELEVATION OF BOTTOM OF AQUIFER , IN FT.
C     PERKH = HORIZONTAL PERMEABILITY ( GPD/SQ FT. )
C     PERKV = VERTICAL PERMEABILITY (GPD/SQ FT. )
C     PERMAQ = PERMEABILITY OF AQUIFER ( GPD/SQ. FT. )
C     PHI = HYDRAULIC HEAD, IN FT.
C     DELX = HORIZONTAL GRID SPACING, IN FT.
C     DELZ = VERTICAL GRID SPACING , IN FT.
C     S = TOTAL LENGTH OF CROSS SECTION , IN FT.
C     ZZERO = ELEVATION OF BOTTOM BOUNDARY OF SECTION , IN FT.
C     ITMAX = MAXIMUM NUMBER OF ITERATIONS
C     TOLER = DESIRED TOLERANCE FOR CONVERGENCE
C     OMEGA = RELAXATION FACTOR
C     ELBOT = ELEVATION OF BOTTOM BOUNDARY OF SECTION, IN FT.
C     NREG = NO. OF RECTANGULAR REGIONS OF EQUAL PERMEABILITY
C     L1,...,L4 = CORNER NODE ABSCISSA NO.,S FOR A RECTANGULAR SECTION
C     K1,...,K4 = CORNER NODE ORDINATE NO.,S FOR A RECTANGULAR SECTION
C     JTABLE = NO. DESIGNATING CLOSEST ORDINATE NODE TO WHICH WATER TABLE LIES
C     KCLASS = NODE CLASS MATRIX FOR DISPERSION EQUATIONS
C     ALPHA = (DELX/DELZ)**2
C     PHIREG = HYDRAULIC HEAD VALUE, IN FT. , FOR A RECTANGULAR REGION
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C     PHIPRV = PREVIOUS VALUE OF PHI, IN FT.
C     PHINEW = UPDATED VALUE OF PHI, IN FT.
C     PHICOR = CORRECTED VALUE OF PHI, IN FT. , AFTER RELAXATION
C     DELPHI = DIFFERENCE BETWEEN PRESENT AND PREVIOUS VALUE OF PHI
C     TOL = ABSOLUTE VALUE OF DELPHI, ABOVE (TOLERENCE)
C     FRAC=FRACTION OF NODES FOR WHICH AN ERROR LARGER
C          THAN TOLERANCE VALUE IS ALLOWED
C     NPER = NO. OF NODES CORRESPONDING TO FRACTION ABOVE
C     PHISYM = SPECIAL VALUE OF PHI DETERMINED FROM SYMMETRY FORMULA
C     PHILO = LOWER BOUND VALUE USED IN EQUIPOTENTIAL CALCULATIONS
C     PHIHI = UPPER BOUND VALUE OF PHI USED IN EQUIPOTENTIAL CALCULATIONS
C     REM1,REM2 =  REMAINDER TERMS USED TO DETERMINE LOCATION OF EQUIPOTENTIALS
C     XORIG = VALUE OF X-COORDINATE AT ORIGIN
C     DHPHI = HORIZONTAL GRADIENT OF PHI
C     DVPHI = VERTICAL GRADIENT OF PHI
C     VELH = HORIZONTAL VELOCITY ( FT/DAY )
C     VELV = VERTICAL VELOCITY ( FT/DAY )
C     VELR = MAGNITUDE OF VELOCITY RESULTANT
C     VH,VV,VR = ABSOLUTE VALUES OF VELH,VELV,VELR ABOVE
C     SINA=SINE OF ANGLE OF RESULTANT VELOCITY
C     THETA=ANGLE OF RESULTANT WITH RESPECT TO POSITIVE
C          HORIZONTAL AXIS, COUNTERCLOCKWISE, IN DEGREES
C     ANGLE = MATRIX USED TO STORE VALUES OF THETA ABOVE
C     IDIV = NO. OF DIVISIONS ALONG HORIZONTAL
C     JDIV = NO. OF DIVISIONS ALONG VERTICAL
C     XMIN = MINIMUM VALUE OF ABSCISSA ,IN FT.
C     XMAX = MAXIMUM VALUE OF ABSCISSA , IN FT.
C     YMIN = MINIMUM VALUE OF ORDINATE , IN FT.
C     YMAX = MAXIMUM VALUE OF ORDINATE , IN FT.
C     L = MATRIX USED TO STORE VALUES OF KCLASS , ABOVE
C     U = HORIZONTAL VELOCITY (POSITIVE TO RIGHT)
C     VY = VERTICAL VELOCITY (POSITIVE DOWNWARD)
C     DCL = DISPERSION COEF ALONG DIRECTION OF FLOW
C     DCT = DISPERSION COEF TRANSVERSE TO DIRECTION OF FLOW
C.....................................................................
C     NUMBERING SYSTEM FOR DISPERSION NODE CLASS MATRIX KCLASS
C     0 = EXTERIOR
C     1 = LEFT BOUNDARY
C     2 = LEFT TOP
C     3 = LEFT BOTTOM
C     4 = TOP
C     5 = BOTTOM
C      6 = RIGHT TOP
C     7 = RIGHT BOTTOM
C     8 = RIGHT BOUNDARY
C     9 = INTERIOR
C     10 = KNOWN CONCENTRATION
C.....................................................................   PHI   7
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,               PHI   9
     2U,VY,ZP,GP,GPC,                                                     PHI  10
     3XMIN,XMAX,IDIV,YMIN,YMAX,JDIV                                       PHI  11
      COMMON/CN/CN1,CN2,CN3
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      DIMENSION C(20,20),CSTAR(20,20),CSS(20,20),U(20,20),VY(20,20)      PHI  12
      DIMENSION L(20,20)                                                  PHI  13
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),    PHI  14
     1 JTABLE(20),KCLASS(20,20)                                           PHI  15
      COMMON/VELOZ/VELH(20,20),VELV(20,20),VELR(20,20),ANGLE(20,20)      PHI  16
      DIMENSION GROUND(20),WTABLE(20),BOTOM(2,20),PERMAQ(2),L1(20),      PHI  17
     1K1(20),L2(20),K2(20),L3(20),K3(20),L4(20),K4(20),TOL(20,20)        PHI  18
C.....................................................................   PHI  19
C     READ IN WATER TABLE DATA
C     READ (NUNGW1) HT1
C     HT1=0.
      HT1=0.
```

```
C     READ (NUNGW2) HT2
      HT2=0.
C     READ (NUNGW3) HT3
      HT3=0.
C     READ IN NITROGEN CONCENTRATIONS
C     READ (NUNGW1) CN1
      CN1=0.
C     READ (NUNGW2) CN2
      CN2=1.
C     READ (NUNGW3) CN3
      CN3=0.
C     REWIND NUNGW1
C     REWIND NUNGW2
C     REWIND NUNGW3
C...........................
      READ (5,100) NROW,NCOL
C     WRITE(6,100) NROW,NCOL
  100 FORMAT (2I3)
C     'NCLASS' CODE IS 0 0 FOR INTERIOR NODES,1 FOR WATER TABLE,
C     2 FOR ABOVE WATER TABLE, 3 FOR NO FLOW BOUNDARY, 4 FOR KNOWN
C     HEAD.
      DO 110 J=1,NROW
C     READ IN FROM BOTTOM TO TOP
      READ (5,120) (NCLASS(I,J) ,I=1,NCOL)
  120 FORMAT (20I1)
  110 CONTINUE
C     WRITE (6,127)
  127 FORMAT ('  FLOW CLASS MATRIX')
      DO 125 J=1,NROW
      JJ=NROW-J+1
C     WRITE (6,126) (NCLASS(I,JJ),I=1,NCOL)
  126 FORMAT (20I1)
  125 CONTINUE
      DO 130 I=1,NCOL
      READ (5,140)  (GROUND(I),WTABLE(I),BOTOM(1,I),BOTOM(2,I))
C     WRITE (6,141) (GROUND(I),WTABLE(I),BOTOM(1,I),BOTOM(2,I))
  140 FORMAT (4F6.2)
  141 FORMAT (4F10.2)
  130 CONTINUE
      DO 150 J=1,NROW
      READ (5,160)  (PERKH(I,J),I=1,NCOL)
C     WRITE (6,161) (PERKH(I,J),I=1,NCOL)
  160 FORMAT (10F5.1)
  161 FORMAT (20F5.1)
  150 CONTINUE
      DO 155 J=1,NROW
      READ (5,164)  (PERKV(I,J),I=1,NCOL)
C     WRITE(6,165)  (PERKV(I,J),I=1,NCOL)
  164 FORMAT (10F5.1)
  165 FORMAT (20F5.1)
  155 CONTINUE
C     OPTION IS TO USE ONE PERMEABILITY PER AQUIFER,BELOW
C     READ (5,170)  (PERMAQ(I),I=1,2)
C     WRITE (6,170) (PERMAQ(I),I=1,2)
C 170 FORMAT(2F5.5)
      DO 180 J=1,NROW
      READ (5,195) (PHI(I,J),I=1,NCOL)
  195 FORMAT (10F5.1)
C     WRITE (6,190) (PHI(I,J),I=1,NCOL)
  190 FORMAT (20F5.1)
C     UNKNOWNS AND POINTS ABOVE WATER TABLE ARE READ
C     IN AS ZEROS,TEMPORARILY.
  180 CONTINUE
C     ADJUST WATER TABLE VALUES USING DATA FROM UNSAT MODELS
      DO 181 I=1,7
      DO 181 J=1,NROW
      IF (NCLASS(I,J).EQ.1) PHI(I,J)=PHI(I,J)+HT1
  181 CONTINUE
```

```
      CO 182 I=13,14
      CU 182 J=1,NROW
      IF (NCLASS(I.J).EQ.1) PHI(I,J)=PHI(I,J)+HT2
  182 CCNTINUE
      CO 183 I=15,NCOL
      CO 183 J=1,NROW
      IF (NCLASS(I,J).EQ.1) PHI(I,J)=PHI(I,J)+HT3
  183 CONTINUE
      REAC (5,200)  DELX,DELZ,S,ZZERO                                   PHI 61
C     WRITE (6,200) DELX,DELZ,S,ZZERO                                   PHI 62
  200 FORMAT (4F10.2)                                                   PHI 63
      REAC (5,210)  ITMAX,TOLER,OMEGA                                   PHI 64
C     WRITE (6,211) ITMAX,TOLER,OMEGA                                   PHI 65
  210 FORMAT (I5,2F5.4)                                                 PHI 66
  211 FORMAT (1X,I5,2F5.2)                                              PHI 67
C     SPECIFY ELEVATICN OF LOWER BOUNDARY,BELOW.                        PHI 68
      READ (5,220) ELBCT                                                PHI 69
C     WRITE (6,220) ELBOT                                               PHI 70
  220 FORMAT (F6.1)                                                     PHI 71
      READ (5,230) NREG                                                 PHI 72
C     WRITE (6,230)NREG                                                 PHI 73
  230 FORMAT (I1)                                                       PHI 74
C     READ J CCORDINATES FOR EACH REGION,STARTING WITH                  PHI 75
C     LOWER LEFT-HAND CORNER,THEN CLOCKWISE.                            PHI 76
      CO 240 I=1,NREG                                                   PHI 77
      REAC (5,250)(L1(I),K1(I),L2(I),K2(I),L3(I),K3(I),L4(I),K4(I))     PHI 78
C     WRITE(6,250)(L1(I),K1(I),L2(I),K2(I),L3(I),K3(I),L4(I),K4(I))     PHI 79
  250 FORMAT (8I2)                                                      PHI 80
  240 CCNTINUE                                                          PHI 81
      CO 270 I=1,NREG                                                   PHI 82
      REAC (5,260)  ( PHI(L1(I),K1(I)), PHI(L2(I),K2(I)),               PHI 83
     1 PHI(L3(I),K3(I)), PHI(L4(I),K4(I)))                              PHI 84
C     WRITE (6,260) ( PHI(L1(I),K1(I)), PHI(L2(I),K2(I)),               PHI 85
C    1 PHI(L3(I),K3(I)), PHI(L4(I),K4(I)))                              PHI 86
  260 FORMAT (4F6.2)                                                    PHI 87
  270 CCNTINUE                                                          PHI 88
      REAC(5,280) (JTABLE(I),I=1,NCOL)                                  PHI 89
      CC 290 JROW=1,NROW                                                PHI 90
      REAC (5,285) (KCLASS(I,JROW),I=1,NCOL)                            PHI 91
C     REAC IN FROM TOP TO BOTTOM IN THIS CASE                           PHI 92
  285 FORMAT (20I2)                                                     PHI 93
  290 CCNTINUE                                                          PHI 94
  280 FORMAT (19I2)                                                     PHI 95
C.............................................................          PHI106
C     CCMPUTE VALUES THAT WILL REMAIN PERMANENT                         PHI107
      ALPHA = (DELX/DELZ)**2                                            PHI108
C     COMPUTE HEAD FOR ALL NODES IN EACH RECTANGULAR REGION             PHI109
      CO 300 M=1,NREG                                                   PHI110
      PHIREG=(PHI(L1(M),K1(M))+PHI(L2(M),K2(M))+PHI(L3(M),K3(M))        PHI111
     1      +PHI(L4(M),K4(M)))/4.                                       PHI112
      K1M=K1(M)                                                         PHI113
      K2M=K2(M)                                                         PHI114
      CO 310 J=K1M,K2M,1                                                PHI115
      L1M=L1(M)                                                         PHI116
      L4M=L4(M)                                                         PHI117
      CO 320 I=L1M,L4M,1                                                PHI118
      IF (NCLASS(I,J).EQ.1)  GO TO 320                                  PHI119
      IF (NCLASS(I,J).EQ.4)  GO TU 320                                  PHI120
      IF (NCLASS(I,J).EQ.2)  GO TO 320                                  PHI121
      PHI(I,J)=PHIREG                                                   PHI122
  320 CONTINUE                                                          PHI123
  310 CCNTINUE                                                          PHI124
  300 CONTINUE                                                          PHI125
C     WRITE OUT INITIAL VALUES OF PHI                                   PHI126
      WRITE (6,325)                                                     PHI127
  325 FORMAT (30X,'INITIAL PHI MATRIX')                                 PHI128
      CO 330  J=1,NROW                                                  PHI129
      K=NRCW+1-J                                                        PHI130
      WRITE (6,340)  (PHI(I,K) , I=1,NCOL)                              PHI131
  340 FORMAT (20F5.1)                                                   PHI132
  330 CONTINUE                                                          PHI133
C...........................................................            PHI134
C     START ITERATIVE PROCESS TO FIND PHI VALUES                        PHI135
      NNODES=NCOL*NROW                                                  PHI136
      DO 400 M=1,ITMAX                                                  PHI137
      NDUMMY=0                                                          PHI138
      DO 450 J=1,NROW                                                   PHI139
      DO 500 I=1,NCOL                                                   PHI140
C     SCAN TO DETERMINE NODE CLASS                                      PHI141
      PHIPRV=PHI(I,J)                                                   PHI142
C     3 TYPES BELOW REMAIN CONSTANT                                     PHI143
      IF (NCLASS(I,J).EQ.2)  GO TO 700                                  PHI144
      IF (NCLASS(I,J).EQ.1)  GO TO 700                                  PHI145
      IF (NCLASS(I,J).EQ.4)  GO TO 700                                  PHI146
C     TYPE BELOW IS INTERIOR                                            PHI147
      IF (NCLASS(I,J).EQ.0)  GO TO 540                                  PHI148
C     REMAINING TYPE IS BOUNDARY NODE                                   PHI149
C                                                                       PHI150
      CALL BOUND (I,J,ALPHA)                                            PHI151
C                                                                       PHI152
      GO TO 700                                                         PHI153
C     COMPUTE PHI VALUE FROM SURROUNDING NODES,BELOW                    PHI154
C     FIRST CHECK FOR ADJACENT NODES WITH PHI=0 (ABOVE                  PHI155
C     WATER TABLE.)                                                     PHI156
  540 IF (PHI(I-1,J).NE.0.)  GO TO 550                                  PHI157
      IF (PHI(I+1,J).NE.0.)  GO TO 550                                  PHI158
C                                                                       PHI159
      CALL TABLE (I,J,ALPHA)                                            PHI160
C                                                                       PHI161
      GO TO 700                                                         PHI162
  550 XNUMER=( PERKH(I-1,J)*PHI(I-1,J)+PERKH(I,J)*PHI(I+1,J)            PHI163
     1 +ALPHA*PERKV(I,J-1)*PHI(I,J-1)+ALPHA*PERKV(I,J)*PHI(I,J+1))       PHI164
      XDENOM= (PERKH(I-1,J) + PERKH(I,J)+ALPHA*PERKV(I,J-1)             PHI165
     1 +ALPHA*PERKV(I,J))                                               PHI166
      PHINEW=XNUMER /XDENOM                                             PHI167
      PHI(I,J)=PHINEW                                                   PHI168
C     PERFORM RELAXATION CORRECTION,BELOW                               PHI169
  700 PHICOR=OMEGA*PHI(I,J) + (1.-OMEGA)*PHIPRV                         PHI170
      PHI(I,J)=PHICOR                                                   PHI171
      DELPHI=PHI(I,J)-PHIPRV                                            PHI172
      TOL(I,J)=ABS(DELPHI)                                              PHI173
  500 CONTINUE                                                          PHI174
  450 CONTINUE                                                          PHI175
C     CHECK THE TOLERANCES, INSURE THAT THEY ARE SMALLER THAN           PHI176
C     STANDARD FOR A CERTAIN LARGE FRACTION OF THE NODES (SPECIFIED     PHI177
C     BELOW)                                                            PHI178
      FRAC=.10                                                          PHI179
      NPER=NNODES*FRAC                                                  PHI180
      DO 800 J=1,NROW                                                   PHI181
      DO 850 I=1,NCOL                                                   PHI182
      IF (TOL(I,J).LE.TOLER)   GO TO 850                                PHI183
      NDUMMY=NDUMMY+1                                                   PHI184
  850 CONTINUE                                                          PHI185
  800 CONTINUE                                                          PHI186
C     TOLERANCE EXIT TEMPORARILY SUSPENDED                              PHI187
C     IF (NDUMMY.LT.NPER)  GO TO 900                                    PHI188
  400 CONTINUE                                                          PHI189
C...........................................................            PHI190
C     WRITE OUT INFORMATION                                             PHI191
  900 WRITE (6,950) M,TOLER                                             PHI192
  950 FORMAT ('1',' NO OF ITERATIONS PERFORMED= ',I5,/,'  DESIRED TOLER PHI193
     1ANCE= ',F6.5)                                                     PHI194
C     COULD WRITE SOME INPUT DATA                                       PHI195
      WRITE (6,970)                                                     PHI196
  970 FORMAT (30X,'TABLE OF PHI VALUES',//)                             PHI197
      WRITE (6,980) (I,I=1,NCOL)                                        PHI198
  980 FORMAT (5X,20I5)
      DO 990 J=1,NROW                                                   PHI199
      K=NROW+1-J                                                        PHI200
      WRITE (6,995)  (J,(PHI(I,K),I=1,NCOL))                            PHI201
  995 FORMAT (I5,20F5.1)                                                PHI202
  990 CONTINUE                                                          PHI203
      CALL EQUIP(I,J,DELX,DELZ,ELBOT,NROW,NCOL)                         PHI204
C     INSERT 'CLEAN-UP' ROUTINES PRIOR TO PLOTTING                      PHI205
C     INSERT PLOTTING ROUTINES                                          PHI206
      CALL VEL(I,J,DELX,DELZ,NROW,NCOL)                                 PHI207
      CALL PRECIS (I,J,DELX,DELZ,NROW,NCOL,ZZERO)                       PHI208
      RETURN                                                            PHI209
      END
      SUBROUTINE BOUND (I,J,ALPHA)                                      PHI212
C     THIS SUBROUTINE SELECTS THE PROPER NUMERICAL EXPRESSION           BOUN   1
C     TO BE USED FOR ANY 'BOUNDARY' NODE.                               BOUN   2
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),  BOUN   3
     1 JTABLE(20),KCLASS(20,20)                                         BOUN   4
C     POINTS ON BOUNDARY ARE THOSE SATISFYING I=1,I=NCOL                BOUN   5
C     AND/OR J=1.  NOTE J=1 HAS 2 CORNER POINTS.                        BOUN   6
      IF (J.NE.1)  GO TO 1000                                           BOUN   7
C     FORMULAS BELOW FOR J=1                                            BOUN   8
      IF (I.EQ.1)  GO TO 1200                                           BOUN   9
      IF (I.EQ.NCOL)  GO TO 1300                                        BOUN  10
      GO TO 1400                                                        BOUN  11
 1200 XNUMER= (2*PERKH(I,J)*PHI(I+1,J)+2*ALPHA*PERKV(I,J)*PHI(I,J+1))   BOUN  12
      XDENOM= (2*PERKH(I,J)+2*ALPHA*PERKV(I,J))                         BOUN  13
      GO TO 1500                                                        BOUN  14
 1300 XNUMER=(2*PERKH(I-1,J)*PHI(I-1,J)+2*ALPHA*PERKV(I,J)*PHI(I,J+1))  BOUN  15
      XDENOM= (2*PERKH(I-1,J) + 2*ALPHA*PERKV(I,J))                     BOUN  16
      GO TO 1500                                                        BOUN  17
 1400 XNUMER= (PERKH(I-1,J)*PHI(I-1,J)+PERKH(I,J)*PHI(I+1,J)            BOUN  18
     1 + 2*ALPHA*PERKV(I,J)*PHI(I,J+1))                                 BOUN  19
      XDENOM= (PERKH(I-1,J)+PERKH(I,J)+2*ALPHA*PERKV(I,J))              BOUN  20
 1500 PHINEW=XNUMER/XDENOM                                              BOUN  21
      GO TO 2000                                                        BOUN  22
C.......................................................................BOUN  23
 1000 IF (I.NE.1)  GO TO 1050                                           BOUN  24
C     FORMULAS BELOW FOR I=1                                            BOUN  25
      XNUMER= (2*PERKH(I,J)*PHI(I+1,J)+ALPHA*PERKV(I,J-1)               BOUN  26
     1 *PHI(I,J-1)+ALPHA*PERKV(I,J)*PHI(I,J+1))                         BOUN  27
      XDENOM= (2*PERKH(I,J)+ALPHA*PERKV(I,J-1)                          BOUN  28
     1 +ALPHA*PERKV(I,J))                                               BOUN  29
      PHINEW=XNUMER/XDENOM                                              BOUN  30
      GO TO 2000                                                        BOUN  31
C.......................................................................BOUN  32
C     FORMULAS BELOW ARE FOR I=NCOL                                     BOUN  33
 1050 XNUMER=(2*PERKH(I-1,J)*PHI(I-1,J)+ALPHA*PERKV(I,J-1)              BOUN  34
     1 *PHI(I,J-1)+ALPHA*PERKV(I,J)*PHI(I,J+1))                         BOUN  35
      XDENOM = (2*PERKH(I-1,J)+ALPHA*PERKV(I,J-1)                       BOUN  36
     1 +ALPHA*PERKV(I,J))                                               BOUN  37
      PHINEW=XNUMER/XDENOM                                              BOUN  38
C.......................................................................BOUN  39
 2000 PHI(I,J)=PHINEW                                                   BOUN  40
      RETURN                                                            BOUN  41
      END                                                               BOUN  42
      SUBROUTINE TABLE (I,J)                                            BOUN  43
C     DETERMINE FORMULA FOR THE CASE WHERE ADJOINING                    TABL   1
C     NODES ARE ABOVE WATER TABLE (PHI=0).                              TABL   2
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),  TABL   3
     1 JTABLE(20),KCLASS(20,20)                                         TABL   4
C     DETERMINE WHETHER LEFT OR RIGHT NODE,OR BOTH, ARE                 TABL   5
C     ABOVE WATER TABLE.  GIMMICK IS THAT IF BOTH ARE ABOVE             TABL   6
C     (PHI=0), THEIR SUM IS ALSO ZERO.                                  TABL   7
      SUM=(PHI(I-1,J) + PHI(I+1,J))                                     TABL   8
      IF (SUM.GT.0.)  GO TO 4000                                        TABL   9
C     COMPUTE PHI FOR THE CASE OF BOTH ZERO.  SET EQUAL TO              TABL  10
C     ARITHMETIC MEAN,BELOW.  THIS IS TEMPORARY FORMULA.                TABL  11
                                                                        TABL  12
      PHI(I,J)=  (PHI(I-1,J)+PHI(I+1,J))/2.                             TABL  13
      GO TO 5000                                                        TABL  14
 4000 IF (PHI(I+1,J).EQ.0.)  GO TO 5500                                 TABL  15
C     PERFORM FOR LEFT NODE PHI=0.                                      TABL  16
      PHISYM=(PHI(I,J+1) + PHI(I-1,J-1)) /2.                            TABL  17
C     FORMULA BELOW GOOD FOR HOMOGENEOUS MEDIUM ONLY.                   TABL  18
      XNUMER = (8*PHISYM+4*PHI(I+1,J) + 3*(PHI(I,J+1)+                  TABL  19
     1 PHI(I,J-1)))                                                     TABL  20
      XDENOM=18.                                                        TABL  21
      PHI(I,J)=XNUMER/XDENOM                                            TABL  22
      GO TO 5000                                                        TABL  23
C     PERFORM FOR RIGHT NODE PHI=0.                                     TABL  24
 5500 PHISYM = (PHI(I,J+1)+PHI(I+1,J-1))/2.                             TABL  25
      XNUMER= (8*PHISYM+4*PHI(I-1,J) + 3*(PHI(I,J+1) +                  TABL  26
     1 PHI(I,J-1)))                                                     TABL  27
      XDENOM=18.                                                        TABL  28
      PHI(I,J)=XNUMER/XDENOM                                            TABL  29
 5000 RETURN                                                            TABL  30
      END                                                               TABL  31
      SUBROUTINE EQUIP (I,J,DELX,DELZ,ELBOT,NROW,NCOL)                  EQUI   1
C     THIS SUBROUTINE COMPUTES ELEVATIONS (MSL) OF                      EQUI   2
C     POINTS OF KNOWN HEAD, BY INTERPOLATION, FOR EACH COLUMN           EQUI   3
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),  EQUI   4
     1 JTABLE(20),KCLASS(20,20)                                         EQUI   5
C     SPECIFY LOWER AND UPPER BOUNDS FOR HEAD, BELOW                    EQUI   6
      PHILO=50.                                                         EQUI   7
      NL=PHILO                                                          EQUI   8
      PHIHI=125.                                                        EQUI   9
      NH=PHIHI                                                          EQUI  10
C     SCAN ALL COLUMNS FOR EACH HEAD VALUE                              EQUI  11
C     HERE, INCREMENT IS 5 FT.                                          EQUI  12
      WRITE (6,105)                                                     EQUI  13
  105 FORMAT ('1',//,5X,'LOCATION OF EQUIPOTENTIAL POINTS IN GRID SYSTEMEQUI  14
     1 ')                                                               EQUI  15
      DO 100 L=NL,NH,5                                                  EQUI  16
      DO 200 I=1,NCOL                                                   EQUI  17
      JTAB=JTABLE(I)-1                                                  EQUI  18
      DO 300 J=1,JTAB                                                   EQUI  19
      REM1=PHI(I,J)-L                                                   EQUI  20
      IF (REM1.GE.0.) MM=1                                              EQUI  21
      IF (REM1.LT.0.) MM=0                                              EQUI  22
      REM2=PHI(I,J+1)-L                                                 EQUI  23
      IF (REM2.GE.0.) NN=1                                              EQUI  24
      IF (REM2.LT.0.) NN=0                                              EQUI  25
      NSUM=MM+NN                                                        EQUI  26
      IF (NSUM.NE.1) GO TO 300                                          EQUI  27
C     WHEN HEAD VALUE FALLS BETWEEN NODES, INTERPOLATE                  EQUI  28
C     TO FIND ELEVATION                                                 EQUI  29
      R1=ABS(REM1)                                                      EQUI  30
      R2=ABS(REM2)                                                      EQUI  31
      ZINT= (R1*DELZ)/(R1+R2)                                           EQUI  32
      ZL= ELBOT + (J-1)*DELZ + ZINT                                     EQUI  33
      IF (NCLASS (I,J).EQ.2)  GO TO 300                                 EQUI  34
      IF(NCLASS(I,J+1).EQ.2)  GO TO 300                                 EQUI  35
      WRITE(6,400) L,I,J,ZL                                             EQUI  36
  400 FORMAT (2X,'PHI=',I3,'COL=',I3,'ROW=',I3,'ELEV=',F7.2)            EQUI  37
  300 CONTINUE                                                          EQUI  38
  200 CONTINUE                                                          EQUI  39
  100 CONTINUE                                                          EQUI  40
      WRITE (6,450)                                                     EQUI  41
  450 FORMAT ('1',20X,'INTERPOLATIONS IN THE HORIZONTAL')               EQUI  42
C     SCAN ALL ROWS FOR EACH HEAD VALUE                                 EQUI  43
      XORIG=0.                                                          EQUI  44
      ITMAX=NCOL-1                                                      EQUI  45
      DO 500 L=NL,NH,5                                                  EQUI  46
      DO 600 J=1,NROW                                                   EQUI  47
      DO 700 I=1,ITMAX                                                  EQUI  48
      REM1=PHI(I,J)-L                                                   EQUI  49
      IF (REM1.GE.0.) MM=1
      IF (REM1.LT.0.) MM=0
      REM2=PHI(I+1,J)-L
      IF (REM2.GE.0.) NN=1
      IF (REM2.LT.0.) NN=0
      NSUM=MM+NN
      IF (NSUM.NE.1) GO TO 700
C     WHEN HEAD VALUE FALLS BETWEEN NODES, INTERPOLATE
C     TO FIND HORIZONTAL POSITION.
      R1=ABS(REM1)
      R2=ABS(REM2)
      XINT=(R1*DELX)/(R1+R2)
      XL=XORIG+(I-1)*DELX+XINT
      IF (NCLASS(I,J).EQ.2)  GO TO 700
      IF (NCLASS(I+1,J).EQ.2)  GO TO 700
      WRITE (6,800) L,I,J,XL
  800 FORMAT (2X,'PHI=',I3,'COL=',I3,'ROW=',I3,'X=',F8.1)
  700 CONTINUE
  600 CONTINUE
  500 CONTINUE
      RETURN
      END
      SUBROUTINE VEL (I,J,DELX,DELZ,NROW,NCOL)
C     THIS SUBROUTINE COMPUTES THE VELOCITY VECTOR AT
C     EACH NODE IN THE GRID SYSTEM (EXCEPT AT THE BOUNDARY NODES.)
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),
     1 JTABLE(20),KCLASS(20,20)
      COMMON/VELOZ/VELH(20,20),VELV(20,20),VELR(20,20),ANGLE(20,20)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,
     3XMIN,XMAX,IDIV,YMIN,YMAX,JDIV
      DIMENSION C(20,20),CSTAR(20,20),CSS(20,20),U(20,20),VY(20,20)
      DIMENSION L(20,20)
C     INITIALIZE VELOCITIES TO ZERO
      DO 50 I=1,NCOL
      DO 50 J=1,NROW
      VELH(I,J)=0.
      VELV(I,J)=0.
   50 CONTINUE
      DO 100 I=1,NCOL
      DO 200 J=1,NROW
C     'STAR' OUT ALL NON-INTERIOR NODES.
      IF (NCLASS(I,J).EQ.2) VELV(I,J)=9999999.
      IF (NCLASS(I,J).EQ.2) VELH(I,J)=9999999.
      IF (NCLASS(I,J).EQ.2) VELR(I,J)=9999999.
      IF (NCLASS(I,J).EQ.2) ANGLE(I,J)=9999999.
      IF(NCLASS(I,J).EQ.2.) GO TO 200
C     SET HORIZONTAL AND VERTICAL VELOCITIES AT ZERO AT NO-FLOW BOUNDARY
      IF (NCLASS(I,J).EQ.3)  VELV(I,J)=0.
      IF (NCLASS(I,J).EQ.3)  VELH(I,J)=0.
      IF (NCLASS(I,J).EQ.3)  VELR(I,J)=0.
      IF (NCLASS(I,J).EQ.3)  ANGLE(I,J)=0.
      IF (NCLASS(I,J).EQ.3)  GO TO 200
      JROW=NROW+1-J
      IF (KCLASS(I,JROW).NE.9)  GO TO 150
C     USE 2-POINT FORMULA FOR NUMERICAL DIFFERENTIATION
C     FIND PHI GRADIENT IN HORIZ.,VERTICAL
      DHPHI =-(PHI(I+1,J)-PHI(I-1,J))/(2.*DELX)
      DVPHI =-(PHI(I,J+1)-PHI(I,J-1))/(2.*DELZ)
C     COMPUTE VELOCITIES IN FT/DAY
      VELH(I,J) = PERKH(I,J)*0.134*DHPHI
      VELV(I,J) = PERKV(I,J)*0.134*DVPHI
      GO TO 180
C     DETERMINE HORIZONTAL GRADIENTS
  150 IF (KCLASS(I,JROW).EQ.2)  DH=0.
      IF (KCLASS(I,JROW).EQ.4)  DH=0.
      IF (KCLASS(I,JROW).EQ.6)  DH=0.
      IF (KCLASS(I,JROW).EQ.1)  DH=-(PHI(I+1,J) - PHI(I,J))/DELX
      IF (KCLASS(I,JROW).EQ.3)  DH=-(PHI(I+1,J) - PHI(I,J))/DELX
      IF (KCLASS(I,JRCW).EQ.7)  DH=-(PHI(I,J)-PHI(I-1,J))/DELX
      IF (KCLASS(I,JROW).EQ.8)  DH=-(PHI(I,J)-PHI(I-1,J))/DELX
      IF (KCLASS(I,JROW).EQ.5)   CH=-(PHI(I+1,J)-PHI(I-1 ,J))/(2.*DELX)
C     FOR PCLLUTANT INPUT POINTS,GRADIENT NOT USED IN QUALITY
C     CALCULATIONS IN 'GWQUAL', SO SET TO ZERO FOR CONVENIENCE
      IF (KCLASS(I,JRCW).EQ.10)  CH=0.
C     CETERMINE VERTICAL GRADIENTS
      IF (KCLASS(I,JROW).EQ.3) DV=-(PHI(I,J+1)-PHI(I,J))/DELZ
      IF (KCLASS(I,JROW).EQ.5) DV=-(PHI(I,J+1)-PHI(I,J))/DELZ
      IF (KCLASS(I,JRCW).EQ.7) DV=-(PHI(I,J+1)-PHI(I,J))/DELZ
      IF (KCLASS(I,JROW).EQ.1 )  CV=-(PHI(I,J+1)-PHI(I,J-1))/(2.*DELZ)  VEL  34
      IF (KCLASS(I,JRCW).EQ.8 )  CV=-(PHI(I,J+1)-PHI(I,J-1))/(2.*DELZ)  VEL  35
      IF (KCLASS(I,JRCW).EQ.2)  DV=-(PHI(I,J)-PHI(I,J-1))/DELZ          VEL  36
      IF (KCLASS(I,JRCW).EQ.4)  DV=-(PHITI,J)-PHI(I,J-1))/DELZ          VEL  37
      IF (KCLASS(I,JROW).EQ.6)  DV=-(PHI(I,J)-PHI(I,J-1))/DELZ          VEL  38
C     FOR POLLUTANT INPUT POINTS,GRADIENT NOT USED IN QUALITY
C     CALCULATIONS IN 'GWQUAL', SO SET TO ZERO FOR CONVENIENCE
      IF (KCLASS(I,JRCW).EQ.1C)  DV=0.
      CHPHI=CH
      CVPHI=DV                                                          VEL  39
      VELH(I,J)=PERKH(I,J)*0.134*CHPHI
      VELV(I,J)=PERKV(I,J)*0.134*DVPHI                                  VEL  40
C     COMPUTE VECTOR SUM (RESULTANT)                                    VEL  41
  180 SUMSQ= (VELH(I,J)**2) + (VELV(I,J)**2)                            VEL  42
      VELR(I,J)= SGRT(SUMSQ)                                            VEL  43
      IF(VELH(I,J).GE.O.) MM=1                                          VEL  44
      IF(VELH(I,J).LT.O.) MM=C                                          VEL  45
      IF(VELV(I,J).GE.O.) NN=1                                          VEL  46
      IF(VELV(I,J).LT.O.) NN=0                                          VEL  47
      MNSUM= MM+NN                                                      VEL  48
      VH=VELH(I,J)                                                      VEL  49
      VH= ABS(VH)                                                       VEL  50
      VV=VELV(I,J)                                                      VEL  51
      VV= ABS(VV)                                                       VEL  52
      VR = VELR(I,J)                                                    VEL  53
      VR = ABS(VR)                                                      VEL  54
      IF (VR.LT.0.1E-12)  VR=0.1E-12
      SINA = VV/VR                                                      VEL  56
      A = ARSIN(SINA)*180./3.1416                                       VEL  57
C     START SEPARATING INTO QUADRANTS                                   VEL  58
      NDUMMY = MNSUM-1.                                                 VEL  59
      IF(NCUMMY) 300,400,500                                            VEL  60
  300 THETA = 180. + A                                                  VEL  61
C     3RD CUADRANT                                                      VEL  62
      GO TO 600                                                         VEL  63
  400 IF(VELV(I,J).LT.0.) GO TO 450                                     VEL  64
C     CISTINGUISH BETWEEN 2ND AND 4TH QUADRANT, ABOVE                   VEL  65
      THETA = 180. - A                                                  VEL  66
      GO TC 700                                                         VEL  67
  450 THETA = 360. - A                                                  VEL  68
  700 GO TC 600                                                         VEL  69
  500 THETA = A                                                         VEL  70
C     1ST CUADRANT                                                      VEL  71
  600 ANGLE(I,J) = THETA                                                VEL  72
  200 CONTINUE                                                          VEL  73
  100 CONTINUE                                                          VEL  74
C     WRITE OUT VELOCITY AND ANGLE                                      VEL  75
      WRITE (6,800)                                                     VEL  76
  800 FORMAT ('1',//,30X,'VELOCITY -FT/DAY - AND ANGLE - DEG - MATRIX') VEL  77
      WRITE (6,850) (I,I=1,NCOL)                                        VEL  78
  850 FORMAT (20I6)                                                     VEL  79
      CO 900 J=1,NROW                                                   VEL  80
      K=NRCW+1-J                                                        VEL  81
      WRITE (6,910) (VELR(I,K),I=1,NCOL)                                VEL  82
  910 FORMAT (20F6.1)                                                   VEL  83
      WRITE (6,920) (ANGLE(I,K),I=1,NCOL)                               VEL  84
  920 FORMAT (20F6.1,//)                                                VEL   85
  900 CONTINUE                                                          VEL   86
      RETURN                                                            VEL   87
      END                                                               VEL   88
      SUBROUTINE PRECIS (I,J,DELX,DELZ,NROW,NCOL,ZZERO)                 PRED   1
C     THIS SUBROUTINE PREPARES THE INPUT INTO THE                       PRED   2
C     GROUNDWATER DISPERSION MODEL                                      PRED   3
      COMMON/FINIT/NCLASS(20,20),PERKH(20,20),PERKV(20,20),PHI(20,20),  PRED   4
     1 JTABLE(20),KCLASS(20,20)                                         PRED   5
      COMMON/VELOZ/VELH(20,20),VELV(20,20),VELR(20,20),ANGLE(20,20)     PRED   6
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,              PRED   8
     2U,VY,ZP,GP,GPC,                                                   PRED   9
     3XMIN,XMAX,IDIV,YMIN,YMAX,JDIV                                     PRED  10
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
      DIMENSION C(20,20),CSTAR(20,20),CSS(20,20),U(20,20),VY(20,20)     PRED  11
      DIMENSION L(20,20)                                                PRED  12
      DIMENSION PERMH(20,20),PERMV(20,20)
C.............................................                          PRED  13
C     SET INDEXES FOR ROWS AND COLUMNS                                  PRED  14
      IDIV=NCOL-1                                                       PRED  15
      JDIV=NROW-1                                                       PRED  16
      II=NCOL                                                           PRED  17
      JJ=NROW                                                           PRED  18
C     SET BOUNDARIES IN BOTH DIMENSIONS                                 PRED  19
      XMIN=0.                                                           PRED  20
      XMAX=DELX*(NCOL-1)                                                PRED  21
      YMIN=ZZERO                                                        PRED  22
      YMAX=ZZERO+DELZ*(NROW-1)                                          PRED  23
C     TRANSFER NODE INFORMATION TO K-MATRIX                             PRED  24
      DO 700 I=1,NCOL                                                   PRED  25
      DO 750 JROW=1,NROW                                                PRED  26
      L(I,JROW)=KCLASS(I,JROW)                                          PRED  27
  750 CONTINUE                                                          PRED  28
  700 CONTINUE                                                          PRED  29
C     SET UP ARRAYS FOR VERTICAL AND HORIZONTAL                         PRED  30
C     VELOCITIES                                                        PRED  31
      DO 800 I=1,NCOL                                                   PRED  32
      DO 850 JROW=1,NROW                                                PRED  33
      J=NROW+1-JROW                                                     PRED  34
      U(I,JROW)=VELH(I,J)/86400.                                        PRED  35
      VY(I,JROW)=-VELV(I,J)/86400.                                      PRED  36
      PERMH(I,JROW)=PERKH(I,J)
      PERMV(I,JROW)=PERKV(I,J)
  850 CONTINUE                                                          PRED  37
  800 CONTINUE                                                          PRED  38
C.............................................                          PRED  39
C     WRITE OUT DATA FOR INTERFACE WITH DISPERSION MODEL.               PRED  40
      WRITE (6,900)                                                     PRED  41
  900 FORMAT ('1',20X,'INTERFACE DATA LISTING')                         PRED  42
      WRITE (6,910) II,JJ                                               PRED  43
  910 FORMAT (2I5)                                                      PRED  44
      WRITE (6,920)                                                     PRED  45
  920 FORMAT (20X,'VERTICAL VELOCITIES IN FT/SEC')                      PRED  46
      DO 925 JROW=1,NROW                                                PRED  47
      WRITE (6,930) (VY(I,JROW),I=1,NCOL)                               PRED  48
  930 FORMAT (10E8.2)                                                   PRED  49
  925 CONTINUE                                                          PRED  50
      WRITE (6,940)                                                     PRED  51
  940 FORMAT (20X,'HORIZONTAL VELOCITIES IN FT/SEC')                    PRED  52
      DO 945 JROW=1,NROW                                                PRED  53
      WRITE (6,950) (U(I,JROW),I=1,NCOL)                                PRED  54
  950 FORMAT (10E8.2)                                                   PRED  55
  945 CONTINUE                                                          PRED  56
      WRITE (6,960)                                                     PRED  57
  960 FORMAT ('1',20X,'DISPERSION NODE CLASS MATRIX')                   PRED  58
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```
      DO 965 JROW=1,NROW                                                  PRED 59
      WRITE (6,970) (L(I,JROW),I=1,NCOL)                                  PRED 60
  970 FORMAT (20I2)                                                       PRED 61
  965 CONTINUE                                                            PRED 62
C..........................................................              PRED 63
C     WRITE INTERFACE INFORMATION ON CARDS                                PRED 64
C     WRITE (7,1001)  IDIV,XMIN,XMAX                                      PRED 65
 1001 FORMAT (I5,2F10.2)                                                  PRED 66
C     WRITE (7,1001)  JDIV,YMIN,YMAX                                      PRED 67
      DO 599 J=1,JJ                                                       PRED 69A
C     WRITE (7,651)  (L(I,J),I=1,II)                                      PRED 70
      WRITE (NGWIF)  (L(I,J),I=1,II)
  651 FORMAT (40I2)                                                       PRED 71
  599 CONTINUE                                                            PRED 71A
      DO 601 J=1,JJ                                                       PRED 72
C     WRITE (7,602)  (U(I,J),I=1,II)                                      PRED 73
      WRITE (NGWIF)  (U(I,J),I=1,II)
  602 FORMAT (10E8.2)                                                     PRED 74
  601 CONTINUE                                                            PRED 75
      DO 605 J=1,JJ                                                       PRED 76
C     WRITE (7,606)  (VY(I,J),I=1,II)                                     PRED 77
      WRITE (NGWIF)  (VY(I,J),I=1,II)
  606 FORMAT (10E8.2)                                                     PRED 78
  605 CONTINUE                                                            PRED 79
      DO 611 J=1,JJ
C     WRITE (7,612) (PERMH(I,J),I=1,II)
      WRITE (NGWIF) (PERMH(I,J),I=1,II)
  612 FORMAT (10E8.2)
  611 CONTINUE
      DO 615 J=1,JJ
C     WRITE (7,616) (PERMV(I,J),I=1,II)
      WRITE (NGWIF) (PERMV(I,J),I=1,II)
  616 FORMAT (10E8.2)
  615 CONTINUE
      END FILE NGWIF
      REWIND NGWIF
      RETURN                                                              PRED 80
      END                                                                 PRED 81
      SUBROUTINE GWQUAL
C     PROGRAM GWQUAL.
C     COMPUTES CONCENTRATIONS OF A POLLUTANT AT ALL NODES
C     IN A GRID SYSTEM.
C*    DEFINITION OF SYMBOLS
C*********************************************************
C*    A1-A4 WEIGHTING COEFFICIENTS ON THE CONVECTIVE TERMS *
C*    B1-B3 WEIGHTING COEFFICIENTS ON THE TIME TERMS       *
C*    CFX BOUNDARY VALUE OF CONCENTRATION                  *
C*    CFY BOUNDARY VALUE OF CONCENTRATION                  *
C*    CLX BOUNDARY VALUE OF CONCENTRATION                  *
C*    CLY BOUNDARY VALUE OF CONCENTRATION                  *
C*    CQUIT REFERENCE VALUE TO END CALCULATIONS            *
C*    DCL=DIFFUSION COEFFICIENT IN THE X DIRECTION         *
C*    DCT=DIFFUSION COEFFICIENT IN THE Y DIRECTION         *
C*    DT=VALUE OF THE TIME STEP                            *
C*    DTIDE=TIME STEP BETWEEN DIFFERENT TIDAL VELOCITIES   *
C*    DTMAX=MAXIMUM VALUE OF DT                            *
C*    DTMIN=MINIMUM VALUE OF DT                            *
C*    DTSTEP=MULTIPLIER FOR SUCCESSIVE TIME STEPS          *
C*    DX=GRID SPACE INTERVAL IN THE X DIRECTION            *
C*    DY=GRID SPACE INTERVAL IN THE Y DIRECTION            *
C*    IDIV=NUMBER OF GRID SPACES IN THE X DIRECTION        *
C*    JDIV=NUMBER OF GRID SPACES IN THE Y DIRECTION        *
C*    II=NUMBER OF GRID POINTS IN THE X DIRECTION          *
C*    JJ=NUMBER OF GRID POINTS IN THE Y DIRECTION          *
C*    ICOUNT=COUNTER FOR THE NUMBER OF TIME STEPS          *
C*    IFREQ=FREQUENCY FOR READING NEW TAPE VELOCITIES      *
C*    ITIDE=REFERENCE PARAMETER BETWEEN MAIN AND VCALC     *
C*    IQUIT,JQUIT=SUBSCRIPTS FOR THE REFERENCE POINT       *
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C*     ISET,JSET=COURDINATES FOR POINTS OF INPUT ON BOUNDARY*
C*     JMIN,JMAX=LIMITING POINTS FOR INPUT ON THE BOUNDARY  *
C*     KIN=INTEGER SPECIFYING THE TYPE OF INPUT             *
C*     KFX=INTEGER SPECIFYING THE B.C. ON THE LEFT BOUNDARY *
C*     KFY=INTEGER SPECIFYING THE B.C. ON THE TOP BOUNDARY  *
C*     KLX=INTEGER SPECIFYING THE B.C. ON THE RT. BOUNDARY  *
C*     KLY=INTEGER SPECIFYING THE B.C. ON THE BOT. BOUNDARY *
C*     NHR=INTEGER SPECIFYING THE TIME FOR PRINTING         *
C*     NN=NUMBER OF TIME STEPS                              *
C*     BETAX,BETAY=COEFFICIENTS IN THE TRI-DIAGONAL MATRIX  *
C*     GX,GY=COEFFICIENTS IN THE TRI-DIAGONAL MATRIX        *
C*     ZX,ZY=COEFFICIENTS IN THE TRI-DIAGONAL MATRIX        *
C*     ZP,GP,GPC=VARIABLES USED IN THE THOMAS ALGORITHM     *
C*     DEL1-DEL10=R.H.S. COEFFICIENTS                       *
C*     RO1-RO3=R.H.S. COEFFICIENTS                          *
C*     P1-P3,Q1-Q3,S1-S3=R.H.S. COEFFICIENTS                *
C*     TIDE=TIME TO CALL UP A NEW TIDAL VELOCITY FIELD      *
C*     TINPUT=LENGTH OF TIME OF INPUT                       *
C*     U=VELOCITY FIELD IN THE X DIRECTION                  *
C*     VY=VELOCITY IN THE Y DIRECTION                       *
C*     VEL=NAME OF THE TIDAL VELOCITY FIELD ON TAPE         *
C*     L(I,J)= SPECIFIES THE GEOMETRIC CONFIGURATION        *
C*     C(I,J)=RESULTING CONCENTRATION FIELD                 *
C*     CSTAR(I,J)=INTERMEDIATE CONCENTRATION FIELD          *
C*     CSS(I,J)=INTERMEDIATE CONCENTRATION FIELD            *
C---------------------------
C      NUMBERING SYSTEM FOR DISPERSION NODE CLASS MATRIX KCLASS
C      0 = EXTERIOR
C      1 = LEFT BOUNDARY
C      2 = LEFT TOP
C      3 = LEFT BOTTOM
C      4 = TOP
C      5 = BOTTOM
C      6=RIGHT TOP
C      7 = RIGHT BOTTOM
C      8 = RIGHT BOUNDARY
C      9 = INTERIOR
C      10 = KNOWN CONCENTRATION
C---------------------------
C*******************************************************
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34) ,VY(46,34)
      DIMENSION L(23,21),VEL(49,34)
      DIMENSION GX(23),ZX(23)
      DIMENSION GY(21),ZY(21)
      DIMENSION PERMH(20,20),PERMV(20,20)
      DIMENSION DCL(20,20),DCT(20,20)
      DIMENSION TITLE(10)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT,VEL,
     3XMIN,XMAX,IDIV,YMIN,YMAX,JDIV
      COMMON/FIRST/ZX,BETAX,GX,DEL1,DEL2,DEL3,DEL4,DEL5
      COMMON/SECOND/ZY,BETAY,GY,DEL6,DEL7,DEL8,DEL9,DEL10,RO1,RO2,RO3
      COMMON/THIRD/P1,P2,P3,P4,P5,Q1,Q2,Q3,S1,S2,S3
      COMMON/CN/CN1,CN2,CN3
      COMMON/DSETS/NGWIF,NUNIF1,NUNOV1,NUNRE1,NUNGW1,NUNRE2,NUNIF2,
     1 NUNOV2,NUNOV3,NUNOV4,NUNIF3,NUNGW2,NUNGW3,NOVRE1,NOVRE2,NRERE1,
     2 NRERE2,NOVRE3
C
C READ AND PRINT TITLE
      READ (5, 9000) (TITLE(N),N=1,10)
 9000 FORMAT (10A4)
      WRITE (6,9331) (TITLE(N),N=1,10)
 9331 FORMAT ('1', 10A4///)
C
C GRID SIZE IN THE X DIRECTION
      READ (5,1000) IDIV,XMIN,XMAX,DX
 1000 FORMAT (I5,3F10.5)
```

```
      WRITE (6,2000) XMAX,DX
 2000 FORMAT (' XMAX=',F10.1,5X,'  DX =',F10.4)
C GRIC SIZE IN THE Y CIRECTION
      READ (5,1000) JCIV,YMIN,YMAX,DY
      WRITE (6,2001) YMAX,DY
 2001 FORMAT (' YMAX=',F10.4,5X,'  DY =',F10.4)
C
C SET BOUNCARY CONDITIONS
      REAC (5,2003) KFX,CFX,KLX,CLX
      REAC (5,2003)       KFY,CFY,KLY,CLY
 2003 FORMAT (2(I3,F7.2))
      WRITE (6,2004) KFX,CFX,KLX,CLX
 2004 FORMAT(' KFX=',I3,' CFX=',F7.2,' KLX=',I3,' CLX=',F7.2)
      WRITE (6,2005) KFY,CFY,KLY,CLY
 2005 FORMAT (' KFY=',I3,' CFY=',F7.2,' KLY=',I3,' CLY=',F7.2)
C
C CONVECTIVE TERM WEICHTING COEFFICIENTS.
      REAC(5,1001) A1,A2,A3,A4
 1001 FORMAT (5F10.5)
      WRITE (6,2006) A1,A2,A3,A4
 2006 FORMAT(' A1=',F10.5,' A2=',F10.5,' A3=',F10.5,' A4=',F10.5)
      REAC (5,103) IFREQ,TMAX
  103 FORMAT(I3,F10.5)
C     UNITS OF TMAX ARE CAYS
C
C CONCENTRATION FOR TERMINATION OF CALCULATION
      REAC (5,1004) CCUIT,IQUIT,JQUIT
 1004 FORMAT(F10.5,2I3)
C
C TIME STEP SECUENCE NO. OF STEPS, MIN, MAX, STEP SIZE
      REAC (5,1000) NN,DTMIN,CTMAX,DTSTEP
      WRITE (6,2008) NN,DTMIN,DTMAX,DTSTEP
 2008 FORMAT(' ',I5,' TIME STEPS',' DTMIN= ',F10.4,' DTMAX= ',F10.4,
     1'  CTSTEP= ',F10.4)
C     UNITS CF DTMIN ANC CTMAX MUST BE CONVERTED FROM HOURS TO SEC
      CTMIN=DTMIN*3600.
      CTMAX=DTMAX*3600.
C
C INPUT CCNCENTRATION (TYPE,FROM JMIN TO JMAX)
      REAC (5,1200) KIN,JMIN,JMAX,ISET,JSET,TINPUT
C     UNITS CF TINPUT ARE CAYS
 1200 FORMAT (5I3,F10.5)
      WRITE (6,1500) ISET,JMIN,JMAX
 1500 FORMAT (' INPUT AT I=',I3,' BETWEEN J=',I3,' TO J=',I3)
      WRITE(6,1501) TINPUT
 1501 FCRMAT(' TINPUT=',F10.2)
C
C SPACE INCREMENTS
      CIVJ=JDIV
      CIVI=IDIV
C NUMBER CF GRID POINTS IN X CIRECTION
      II=ICIV+1
C NUMBER OF GRID PCINTS IN THE Y CIRECTION
      JJ=JCIV+1
      WRITE (6,2007) II,JJ
 2007 FORMAT (' II=',I3,' JJ=',I3)
C
C REAC ANC WRITE THE L ARRAY
      WRITE(6,85)
   85 FORMAT(/' L(I,J) ARRAY FOLLOWS')
      IF (II-21) 90,90,95
   90 CO 92 J=1,JJ
C  91 REAC (5,98)(L(I,J),I=1,II)
   91 REAC (NGWIF) (L(I,J),I=1,II)
   92 WRITE (6,99) (L(I,J),I=1,II)
      GO TO 89
   95 CO 97 I=1,II
      IREV=II-I+1
   96 READ (5,98) (L(IREV,J),J=1,JJ)
   97 WRITE(6,99) (L(IREV,J),J=1,JJ)
   98 FORMAT (40I2)
   99 FORMAT (/' ',40I2)
   89 CONTINUE
C
C INITIALIZE ALL B.C. TO ZERO
      DO 100 I=1,II
      DO 100 J=1,JJ
      C(I,J)=0.
      CSTAR(I,J)=0.
      CSS(I,J)=0.
  100 CONTINUE
      CSTART=0.1E-30
C     TEMPORARILY, USE NON-ZERO VALUES TO AVOID UNDERFLOWS
      DO 150 I=1,II
      DO 150 J=1,JJ
      IF (L(I,J).EQ.0)  GO TO 150
      C(I,J)=CSTART
      CSTAR(I,J)=CSTART
      CSS(I,J)=CSTART
  150 CONTINUE
C
C SET THE VELOCITY FIELD
      DO 101 I=1,II
      DO 101 J=1,JJ
      U(I,J)=0.
      VY(I,J)=0.
  101 CONTINUE
C
C FIRST TIME STEP
      DT=DTMIN
C
C SET CONSTANT VALUES
  110 T=0.
      ICOUNT=0
      TIDE=0.
      ITIDE=0
      DTIDE=600*IFREQ
      NHR=18/IFREQ
      DT=DT/DTSTEP
C     CONVERT TMAX AND TINPUT FROM DAYS TO SECONDS
      TMAX=TMAX*86400.
      TINPUT=TINPUT*86400.
      B1=0.6667
      B2=0.1667
      B3=B2
C     INSTEAD OF USING VCALC, READ VELOCITY FIELD BELOW
C     VELOCITIES ARE IN (FT/SEC)
      DO 601 J=1,JJ
C     READ    (5,602) (U(I,J),I=1,II)
      READ (NGWIF)    (U(I,J),I=1,II)
  602 FORMAT (10E8.2)
  601 CONTINUE
      DO 605 J=1,JJ
C     READ  (5,606)  (VY(I,J),I=1,II)
      READ (NGWIF)   (VY(I,J),I=1,II)
  606 FORMAT (10E8.2)
  605 CONTINUE
C     READ IN HORIZONTAL AND VERTICAL PERMEABILITIES
      DO 611 J=1,JJ
C     READ(5,612) (PERMH(I,J),I=1,II)
      READ (NGWIF)(PERMH(I,J),I=1,II)
  612 FORMAT (10E8.2)
  611 CONTINUE
      DO 615 J=1,JJ
C     READ (5,616) (PERMV(I,J),I=1,II)
      READ(NGWIF)  (PERMV(I,J),I=1,II)
  616 FORMAT (10E8.2)
  615 CONTINUE
      REWIND NGWIF
C
C     COMPUTE DISPERSION COEFFICIENTS
C     BASED ON HOOPES AND HARLEMAN FORMULAS
C     FORMULATION BELOW COMPUTES COEFFICIENTS IN (SQ CM/SEC)
      VISKIN=0.00001040
C     VISKIN ABOVE IN (SQ FT/SEC),FOR TEMP 71.5 F
C     CONVERT TO (SQ CM/SEC) BELOW
      VISKIN=VISKIN*0.001075
C     BELOW CONVERT PERMEABILITY IN (GPD/SQ FT) TO (SQ CM)
C     ALSO, CONVERT VELOCITY FROM (FT/SEC) TO (CM/SEC)
      ALPHA3=88.
      BETA3=1.2
      DO 350 I=1,II
      DO 350 J=1,JJ
C     USE ABSOLUTE VALUES OF VELOCITY
      UABS=ABS(U(I,J))*30.5
      VABS=ABS(VY(I,J))*30.5
      PH=PERMH(I,J)*0.542E-9
      PV=PERMV(I,J)*0.542E-9
      TERM1=VISKIN*ALPHA3
      TERM2=(UABS*(PH**0.5))/VISKIN
      DCL(I,J)=TERM1*(TERM2**BETA3)
      TERM3=(VABS*(PV**0.5))/VISKIN
      DCT(I,J)=TERM1*(TERM3**BETA3)
  350 CONTINUE
C     CONVERT DCL AND DCT FROM (SQ CM/SEC) TO (SQ FT/SEC)
      DO 360 I=1,II
      DO 360 J=1,JJ
      DCL(I,J)=DCL(I,J)*0.001075
      DCT(I,J)=DCT(I,J)*0.001075
  360 CONTINUE
C---------------------------------------
C
C BEGIN TIME DO LOOP
C
  400 DO 530 M=1,NN
      DARG=DT
      IF (DARG-DTMAX) 430,420,420
  430 CONTINUE
C BEGIN TIME STEPPING SEQUENCE
      IF(M-3) 402,402,403
  402 DT=M*3600.
      GO TO 419
  403 IF (M-8) 404,405,405
  404 DT=DT*DTSTEP
      GO TO 419
  405 IF(M-11) 406,407,408
  406 DT=48.*3600.
      GO TO 419
  407 DT=120.*3600.
      GO TO 419
  408 IF(M-13) 404,409,420
  409 DT=DTMAX
      GO TO 419
  420 DT=DTMAX
  419 CONTINUE
C
C CHECK FOR SINGLE OR DOUBLE INPUT
C     STATEMENTS BELOW EXCLUDED TEMPORARILY
C     IF (KIN.EQ.1) GO TO 433
C     T1=43200.-DT
C     T2=43200.+TINPUT
C     IF (T.LE.T2.AND.T.GE.T1) GO TO 435
  433 CONTINUE
      IF (T-TINPUT) 435,435,437
  435 CONTINUE
C CALL SUB. CINPUT TO SET INPLT VALUES
      CALL CINPUT(JMIN,JMAX,ISET,JSET,KIN,T,TINPUT)
  437 CCNTINUE
      ICCUNT=ICOUNT+1
      T=T+CT
C
C SAVE C(N) BY STORING IN CSS
      DO 440 I=1,II
      DO 440 J=1,JJ
  440 CSS(I,J)= C(I,J)
C
C----------------------------------------
C     BYPASS USAGE INSTRUCTIONS FOR SUBROUTINE VCALC
C SET UP NEW VEL FIELC AT TIDE INCREMENTS
C     IF (ICOUNT.EQ.1) GO TO 700
C     IF (T.EQ.TIDE) GO TO 700
C     GO TC 800
C 700 CONTINUE
C     CALL VCALC (ITICE)
C     CONTINUE
C 800 CONTINUE
C THREE EGUATICN SCHEME FOR SOLUTION
C SCLVE THE X EQN. FOR CSTAR
      CALL TRIX
  445 CCNTINUE
C RESTCRE C TO C(N) FROM CSS
      CO 480 I=1,II
      CO 480 J=1,JJ
  480 C(I,J)=CSS(I,J)
C SCLVE THE Y EQN. FOR CSS
      CALL TRIY
      CONTINUE
C SCLVE EXPLICITLY FOR C(N+1)
      CALL EXPLIC
  439 CCNTINUE
C PRINT THE CONCENTRATION CIST. IF T EQUALS TIDE
C     IF (ICOUNT.EQ.1) GO TO 250
C     IF (T.EQ.TIDE) GO TO 250
C     GO TC  285
C 250 CONTINUE
C     IF ((ITICE/NHR)*NHR.NE.ITIDE) GO TO 275
C     PRINT OUT RESULTS AT ALL TIME STEPS
      CALL CUTPUT(T,DTMAX)
  275 CONTINUE
      ITICE=ITICE+1
      TICE=TIDE+DTIDE
  285 CCNTINUE
      IF(T-TMAX) 520,540,540
  520 IF (C(IQUIT,JQUIT)-CQUIT) 530,540,540
  530 CONTINUE
  540 CCNTINUE
      RETURN
      END
      SUBROUTINE VCALC(ITICE)
C SUBRCUTINE VCALC
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21),VEL(49,34)
      CIMENSION DCL(20,20),DCT(20,20)
      COMMCN/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICCUNT,VEL
C READ IN VELOCITY FIELD FROM TAPE
      IF (ITIDE) 11,11,21
   11 CONTINUE
      ISKIP=12
      CO 16 NSKIP=1,ISKIP
   16 READ (11) VEL
```

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      DO 18 NFREQ=1,IFREQ
   18 READ (11) VEL
      IWIND =(72-ISKIP)/IFREQ
      GO TO 45
   21 CONTINUE
      IF (ITIDE.EQ.IWIND) GO TO 25
      DO 23 NFREQ=1,IFREQ
   23 READ (11) VEL
      GO TO 45
   25 REWIND 11
      DO 27 NFREQ=1,IFREQ
   27 READ (11) VEL
      IWIND=IWIND+(72/IFREQ)
   45 CONTINUE
      IB=45
      I=IB
      JR=33
      JJM1=JR-1
C TRANSFER VELOCITY FIELD FROM VEL TO U AND VY
C STORE U AND VY FOR ODD-EVEN AND EVEN-ODD POINTS
    5 DO  10 J=2,JJM1,2
      U(I,J)=VEL(I,J)
      VY(I,J)=VEL(I,J+1)
   10 CONTINUE
      I=I-1
      IF (I) 50,50,15
   15 DO  20 J=1,JR,2
      U(I,J)=VEL(I,J)
      VY(I,J)=VEL(I,J+1)
   20 CONTINUE
      I=I-1
      GO TO 5
   50 CONTINUE
C CALC FOR ODD-ODD POINTS
      I=IB
   40 DO 190 J=1,JR,2
      M=I+1
      N=J+1
      MM=(I+1)/2
      NN=(J+1)/2
      K=L(MM,NN)
C K CHECK FOR U AND VY
      IF (K-9)  55, 75, 110
   55 IF (K-1) 100,110, 60
   60 IF (K-3) 120,130,65
   65 IF (K-6) 145,160, 70
   70 IF (K-8) 100,110, 75
   75 U(M,N)= .25*(U(I-1,J)+U(I+1,J)+U(I,J-1)+U(I,J+1))
      VY(M,N)=.25*(VY(I-1,J)+VY(I+1,J)+VY(I,J-1)+VY(I,J+1))
      GO TO 190
  100 U(M,N)=0.
      VY(M,N)=0.
      GO TO 190
  110 U(M,N)=.5*(U(I,J+1)+U(I,J-1))
      VY(M,N)= .5*(VY(I,J+1)+VY(I,J-1))
      IF (I.EQ.45.AND.J.EQ.21) GO TO 170
      GO TO 190
  120 U(M,N)=.500*(U(I,J+1)+U(I+1,J))
      VY(M,N)=.500*(VY(I,J+1)+VY(I+1,J))
      GO TO 190
  130 U(M,N)=.500*(U(I,J-1)+U(I+1,J))
      VY(M,N)=.500*(VY(I,J-1)+VY(I+1,J))
      GO TO 190
  145 U(M,N)=.5*(U(I+1,J)+U(I-1,J))
      VY(M,N)= .5*(VY(I+1,J)+VY(I-1,J))
      GO TO 190
  160 U(M,N)=.500*(U(I,J+1)+U(I-1,J))
      VY(M,N)=.500*(VY(I,J+1)+VY(I-1,J))
      GO TC 190
  170 U(M,N)=.500*(U(I,J-1)+U(I-1,J))
      VY(M,N)=0.
  190 CONTINUE
      I=I-2
      IF (I-1) 350,40,40
  350 CCNTINUE
      CO 700 M=2,46,2
      DO 700 N=2,34,2
      I=M/2
      J=N/2
      U(I,J)=U(M,N)
      VY(I,J)=VY(M,N)
  700 CCNTINUE
C WRITE CUT VELOCITY FIELD
      NHR=18/IFREQ
      IF ((ITICE/NHR)*NHR.NE.ITIDE) GO TO 500
      TIME=ITICE/3
      WRITE (6,410) TIME
      WRITE (6,420)
      CO 400 IR=1,II
      I=II-IR+1
      WRITE (6,401) I,(U(I,J),J=1,17)
  400 WRITE (6,402) (VY(I,J),J=1,17)
  401 FORMAT (' ', 'I=',I2,2X,18F6.2)
  402 FORMAT (' ',6X,18F6.2)
  410 FORMAT ('1',50X,'U AND V VELOCITIES AT TIME=',F8.2,'HRS')
  420 FORMAT ('0','           J=1    J=2    J=3    J=4    J=5    J=6    J=7    J=8
     1    J=9   J=10  J=11  J=12  J=13  J=14  J=15  J=16  J=17  J=18')
  500 CCNTINUE
      CCNTINUE
      RETURN
      ENC
      SUBRCUTINE TRIX
C SUB TRIX
      CIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      CIMENSION DCL(20,20),DCT(20,20)
      CIMENSION GX(23),ZX(23)
      CIMENSION V(23),W(23)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICCUNT
      COMMON/FIRST/ZX,BETAX,GX,DEL1,DEL2,DEL3,DEL4,DEL5
      SUMF(S1,P1,S2,P2,S3,P3,S4,P4,S5,P5)=S1*P1+S2*P2+S3*P3+S4*P4+S5*P5
      CO 280 J=1,JJ
      I=0
   20 I=I+1
      IF (II-I) 280,21,21
   21 K=L(I,J)
      IF (K-1) 20,140,140
  140 M=I
C FIND THE MOST RIGHT BOUND
      I=0
    5 IREV=(II-I)
      IF (L(IREV,J)) 10,10,15
   10 I=I+1
      GO TC 5
   15 IR=IREV
  180 CO 195 I=M,IR
      K=L(I,J)
      IF (J-1) 36,36, 40
   36 JM1=J+1
      GO TO (30,60,70),KFY
   30 SIGM=1.
      SM=0.
      GO TO 100
   60 SIGM=-1.
```

```
      SM=2.
      GO TO 100
   70 CONTINUE
   40 JM1=J-1
      SIGM=1.
      SM=0.
      IF (JJ-J) 55,55,42
C TOP CR BCTTOM
   42 IF (K-9) 45,100,100
   45 IF (K-1) 20,100,46
   46 IF (K-3) 50,55,47
   47 IF(K-5) 50,55,48
   48 IF (K-7) 50,55,100
C TOP CONDITION
   50 JM1=J+1
      GO TC (30,60,70),KFY
      GO TO 100
C BOTTOM CONDITION
   55 JP1=J-1
      GO TC (110,115,120) ,KLY
  110 SIGP=1.
      SP=0.
      GO TC 141
  115 SIGP=-1.
      SP=2.
      GO TC 141
  120 CCNTINUE
  100 JP1=J+1
      SIGP=1.
      SP=0.
  141 CONTINUE
      CALL COEFX(I,J)
      IF (K.EQ.10) GO TO 191
      IF (I-M) 425,425,375
  375 IF (V(I-1)) 400,425,400
C LEFT OR RIGHT
  400 IF (K-1) 450,425,401
  401 IF (K-10) 402,191,425
  402 IF (K-9) 403,450,191
  403 IF (K-4) 425,450,404
  404 IF (K-6) 450,475,475
C LEFT BOUNCARY CONCITION
  425 GO TC (430,431,432),KFX
  430 CIM1J=C(I+1,J)
      CIP1J=C(I+1,J)
      V(I)=BETAX
      GO TC 485
  431 CIM1J=-C(I+1,J)+2.*C(I,J)
      CIP1J=C(I+1,J)
      V(I)= BETAX+2.*ZX(I)
      GO TC 485
  432 CCNTINUE
C R+GHT BCUNDARY CCNDITION
  475 GO TO (480,481,482),KLX
  480 CIP1J=C(I-1,J)
      CIM1J=C(I-1,J)
      V(I)= BETAX-(ZP*GP)/V(I-1)
      GO TO 485
  481 CIP1J=-C(I-1,J)+2.*C(I,J)
      CIM1J=C(I-1,J)
      V(I)= BETAX+2.*GX(I)-(ZP*GP)/V(I-1)
      GO TC 485
  482 CONTINUE
C INTERICR CCNCITION
  450 CIP1J=C(I+1,J)
      CIM1J=C(I-1,J)
      V(I)= BETAX-(ZP*GP)/V(I-1)
  485 CCNTINUE
```

```
      CIJ=C(I,J)
      CIJM1=SIGM*C(I,JM1)+SM*C(I,J)
      CIJP1=SIGP*C(I,JP1)+SP*C(I,J)
      RHS =      SUMF(DEL1,CIM1J,DEL2,CIJ,DEL3,CIP1J,DEL4,CIJM1,DEL5,
     1CIJP1)
      ID=1
      IN=2
  172 IF (I-M) 186,186,187
  187 IF (V(I-1)) 188,186,188
  186 W(I)=RHS
      GO TO 189
  188 W(I)=RHS-(W(I-1)*ZP)/V(I-1)
  189 CONTINUE
C CHECK FOR TYPE 2 B.C.
      GO TO 195
  191 W(I)=C(I,J)
      V(I)=BETAX
  195 CONTINUE
C     WRITE OUT W AND V , TEMPORARILY
C     WRITE (6,2500) (W(I),I=1,II)
C     WRITE (6,2500) (V(I),I=1,II)
 2500 FORMAT (10E8.2)
C BEGIN CSTAR CALCULATION
      CSTAR(IR,J)=W(IR)/V(IR)
      ISOL=IR-M
      DO 240 I=1,ISOL
      IREV=IR-I
      CALL COEFX(IREV,J)
      IF (V(IREV)) 230,210,230
  210 CSTAR(IREV,J)=0.0
      GO TO 240
  230 CSTAR(IREV,J) = (W(IREV)-GPC * CSTAR(IREV+1,J))/V(IREV)
  240 CONTINUE
  280 CONTINUE
 2000 CONTINUE
      RETURN
      END
      SUBROUTINE COEFX(I,J)
C SUB COEFX
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION DCL(20,20),DCT(20,20)
      DIMENSION GX(23),ZX(23)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
      COMMON/FIRST/ZX,BETAX,GX,DEL1,DEL2,DEL3,DEL4,DEL5
      DXSQ=DX*DX
      DYSQ=DY*DY
   21 K=L(I,J)
      IF(K-10)9,9,70
    9 CONTINUE
      ZX(I)=B3/DT-DCL(I,J)/DXSQ-(A4*U(I,J))/DX
      BETAX=B1/DT+2.0*DCL(I,J)/DXSQ+(A4-A3)*U(I,J)/DX
      GX(I)=B2/DT-DCL(I,J)/DXSQ +A3*U(I,J)/DX
      DEL1=B3/DT+A2*U(I,J)/DX
      DEL2=B1/DT-2.0*DCT(I,J)/DYSQ+(A1-A2)*U(I,J)/DX
      DEL3=B2/DT-A1*U(I,J)/DX
      DEL4=DCT(I,J)/DYSQ+VY(I,J)/(2.0*DY)
   10 DEL5=DCT(I,J)/DYSQ-VY(I,J)/(2.0*DY)
C     WRITE (6,3500) I,J,DEL4,DEL5
 3500 FORMAT (2I5,2E8.2)
C LEFT OR RIGHT
      IF (K-9) 11,50,42
   11 IF (K-1) 20,33,12
   12 IF (K-4) 33,50,13
   13 IF (K-6) 50,34,34
C ONE STEP BEYOND B.C.
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```
   50 IF (L(I-1,J)-10) 51,59,57
   51 IF (L(I-1,J)- 9) 55,60,59
   55 IF (L(I-1,J)-1) 20,57,56
   56 IF (L(I-1,J)-4) 57,60,60
   57 ZP=ZX(I)
      GO TO (52,53,54),KFX
   52 GP=GX(I-1)+ZX(I-1)
      GPC=GX(I)
      GO TO 100
   53 GP=GX(I-1)-ZX(I-1)
      GPC=GX(I)
      GO TO 100
   54 CONTINUE
   59 ZP=ZX(I)
      GP=0.
      GPC=GX(I)
      GO TO 100
C INTERIOR CONDITION
   60 ZP=ZX(I)
      GP=GX(I)
      GPC=GX(I)
      GO TO 100
   20 ZP=0.
      BETAX=0.
      GP=0.
      GPC=0.
      GO TO 100
C LEFT CONDITION
   33 ZP=0.
      GP=0.
      GO TO (35,36,37),KFX
   35 GPC=GX(I)+ZX(I)
      GO TO 100
   36 GPC=GX(I)-ZX(I)
      GO TO 100
   37 CONTINUE
C RIGHT CONDITION
   34 GP=GX(I-1)
      GO TO (38,39,40),KLX
   38 ZP=ZX(I)+GX(I)
      GPC=0.
      GO TO 100
   39 ZP=ZX(I)-GX(I)
      GPC=0.
      GO TO 100
   40 CONTINUE
   42 IF (K-10) 43,43,70
   43 ZP=0.
      GP=0.
      GPC=0.
      BETAX=1.0
      GO TO 100
   70 ZP=0.
  100 CONTINUE
      RETURN
      END
      SUBROUTINE TRIY
C SUB TRIY
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION DCL(20,20),DCT(20,20)
      DIMENSION GY(21),ZY(21)
      DIMENSION V(23),W(23)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
      COMMON/SECOND/ZY,BETAY,GY,DEL6,DEL7,DEL8,DEL9,DEL10,RO1,RO2,RO3
      SUMF(S1,P1,S2,P2,S3,P3,S4,P4,S5,P5)=S1*P1+S2*P2+S3*P3+S4*P4+S5*P5
      M=1
      CO 550 I=M,II
      J=0
   20 J=J+1
      IF (JJ-J) 550,21,21
   21 K=L(I,J)
      IF (K-1) 20,140,140
  140 N=J
C FIND THE LOWEST BOUND
      J=0
    5 JREV=JJ-J
      IF (L(I,JREV)) 10,10,15
   10 J=J+1
      GC TC 5
   15 JBCT=JREV
  450 CO 465 J=N,JBOT
      K=L(I,J)
      IF(I-1) 320,320,310
  320 IM1=M+1
      GC TC (330,331,332),KFX
  330 SIGM=1.
      SM=0.
      GO TC 370
  331 SIGM=-1.
      SM=2.
      GO TC 370
  332 CONTINUE
  310 IM1=I-1
      SIGM=1.
      SM=0.
      IF (II-I) 58,58,42
C LEFT OR RIGHT
   42 IF (K-9) 45,370,370
   45 IF (K-1) 20,57,46
   46 IF (K-4) 57,370,47
   47 IF (K-6) 370,58,58
C LEFT CCNCITION
   57 IM1=I+1
      GO TC (330,331,332),KFX
C RIGHT CONCITICN
   58 IP1=I-1
      GO TC (380,381,382),KLX
  380 SIGP=1.
      SP=0.
      GO TC 141
  381 SIGP=-1.
      SP=2.
      GO TO 141
  382 CCNTINUE
  370 IP1=I+1
      SIGP=1.
      SP=0.
  141 CONTINUE
      CALL COEFY(I,J)
      IF (K.EQ.10) GO TO 463
      IF (J-N) 475,475,575
  575 IF (V(J-1)) 600,475,600
C TCP CR BCTTOM
  600 IF (K-1) 460,46C,601
  601 IF (K-10) 602,463,475
  602 IF (K-9) 603,46C,463
  603 IF (K-3) 475,485,604
  604 IF (K-5) 475,485,605
  605 IF (K-7) 475,485,460
C TCP CONCITION
  475 GO TC (430,431,432),KFY
  430 CIJM1=C(I,J+1)
      CIJP1=C(I,J+1)
      V(J)=BETAY
      GO TO 455
  431 CIJM1=-C(I,J+1)+2.*C(I,J)
      CIJP1=C(I,J+1)
      V(J)=BETAY+2.*ZY(J)
      GO TO 455
  432 CONTINUE
C BOTTOM CONDITION
  485 GO TO (490,491,492),KLY
  490 CIJP1=C(I,J-1)
      CIJM1=C(I,J-1)
      V(J)=BETAY -(ZP*GP)/V(J-1)
      GO TO 455
  491 CIJP1=-C(I,J-1)+2.*C(I,J)
      CIJM1=C(I,J-1)
      V(J)=BETAY +2.*GY(J)-(ZP*GP)/V(J-1)
      GO TO 455
  492 CONTINUE
C INTERIOR CONDITION
  460 CIJP1=C(I,J+1)
      CIJM1=C(I,J-1)
      V(J)=BETAY -(ZP*GP)/V(J-1)
  455 CONTINUE
      CIJ=C(I,J)
      CIM1J=SIGM*C(IM1,J)+SM*C(I,J)
      CIP1J=SIGP*C(IP1,J)+SP*C(I,J)
      RHS =           SUMF  (DEL6,CIJM1,DEL7,CIJ,DEL8,CIJP1,DEL9,CIM1J,
     1DEL10,CIP1J)
      CSI=CSTAR(I,J)
      CSIM1 =SIGM*CSTAR(IM1,J)+SM*CSTAR(I,J)
      CSIP1 =SIGP*CSTAR(IP1,J)+SP*CSTAR(I,J)
      RHS=RHS+        RO1*CSI+RO2*CSIP1+RO3*CSIM1
      IB=1
      IN=2
  172 IF (J-N) 456,456,457
  457 IF (V(J-1)) 458,456,458
  456 W(J)=RHS
      GO TO 459
  458 W(J)=RHS-(W(J-1)*ZP)/V(J-1)
  459 CONTINUE
C CHECK FOR TYPE 2 B.C.
      GO TO 465
  463 W(J)=C(I,J)
      V(J)=BETAY
  465 CONTINUE
C BEGIN CSS CALCULATION
      CSS(I,JBOT)=W(JBOT)/V(JBOT)
      JSOL=JBOT-N
      DO 520 J=1,JSOL
      JREV=JBOT-J
      CALL COEFY(I,JREV)
      IF (V(JREV)) 510,505,510
  505 CSS(I,JREV)=0.
      GO TO 520
  510 CSS(I,JREV)= (W(JREV)-GPC*CSS(I,JREV+1))/V(JREV)
  520 CONTINUE
  550 CONTINUE
 2000 CONTINUE
      RETURN
      END
      SUBROUTINE COEFY(I,J)
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION DCL(20,20),DCT(20,20)
      DIMENSION GY(21),ZY(21)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
```

```
      COMMON/SECOND/ZY,BETAY,GY,DEL6,DEL7,DEL8,DEL9,DEL10,RO1,RO2,RO3
      DXSQ=DX*DX
      DYSQ=DY*DY
   21 K=L(I,J)
      IF (K-10) 9,9,70
    9 CONTINUE
      ZY(J)=-DCT(I,J)/DYSQ-A4*VY(I,J)/DY+B3/DT
      BETAY=B1/DT+2.0*DCT(I,J)/DYSQ+(A4-A3)*VY(I,J)/DY
      GY(J)=-DCT(I,J)/DYSQ+A3*VY(I,J)/DY + B2/DT
      DEL6=-DCT(I,J)/DYSQ+(A2-.5)*VY(I,J)/DY+B3/DT
      DEL7=2.0*DCT(I,J)/DYSQ-(A2-A1)*VY(I,J)/DY
      DEL8=-DCT(I,J)/DYSQ-(A1-.5)*VY(I,J)/DY+B2/DT
      DEL9=-B3/DT
      DEL10=-B2/DT
      RO1=B1/DT
      RO2=B2/DT
   10 RO3=B3/DT
C TOP OR BOTTOM
      IF (K-9) 11,50,42
   11 IF (K-1) 20,50,12
   12 IF (K-3) 34,33,13
   13 IF(K-5)  34,33,14
   14 IF (K-7) 34,33,50
C ONE STEP BEYOND B.C.
   50 IF(L(I,J-1)-9) 55,60,59
   55 IF(L(I,J-1)-1) 20,60,56
   56 IF(L(I,J-1)-3) 57,60,51
   51 IF(L(I,J-1)-5) 57,60,58
   58 IF(L(I,J-1)-7) 57,60,60
   57 ZP=ZY(J)
      GO TO (52,53,54),KFY
   52 GP=GY(J-1)+ZY(J-1)
      GPC=GY(J)
      GO TO 100
   53 GP=GY(J-1)-ZY(J-1)
      GPC=GY(J)
      GO TO 100
   54 CONTINUE
   59 ZP=ZY(J)
      GP=0.
      GPC=GY(J)
      GO TO 100
C INTERIOR CONDITION
   60 ZP=ZY(J)
      GP=GY(J)
      GPC=GY(J)
      GO TO 100
   20 ZP=0.
      BETAY=0.
      GP=0.
      GPC=0.
      GO TO 100
C TOP CONDITION
   34 ZP=0.
      GP=0.
      GO TO (35;36,37),KFY
   35 GPC=GY(J)+ZY(J)
      GO TO 100
   36 GPC=GY(J)-ZY(J)
      GO TO 100
   37 CONTINUE
C BOTTOM CONDITION
   33 GP=GY(J-1)
      GO TO (38,39,40),KLY
   38 ZP=ZY(J)+GY(J)
      GPC=0.
      GO TO 100
   39 ZP=ZY(J)-GY(J)
```

```
      GPC=0.
      GO TO 100
   40 CONTINUE
   42 ZP=0.
      GP=0.
      GPC=0.
      BETAY=1.0
      GO TO 100
   70 CONTINUE
  100 CONTINUE
      RETURN
      END
      SUBROUTINE EXPLIC
C SUBEXPLIC
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION CTEMP(23)
      DIMENSION DCL(20,20),DCT(20,20)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
      COMMON/THIRD/P1,P2,P3,P4,P5,Q1,Q2,Q3,S1,S2,S3
      N=1
      DO 280 J=N,JJ
      DO 4 I=1,II
    4 CTEMP(I)=0.0
      I=0
   20 I=I+1
      IF (II-I) 280,21,21
   21 K=L(I,J)
      IF (K-1) 20,140,140
  140 M=I
C FIND THE MOST RIGHT BOUND
      I=0
    5 IREV=(II-I)
      IF (L(IREV,J)) 10,10,15
   10 I=I+1
      GO TO 5
   15 IR=IREV
      DO 95 I=M,IR
      K=L(I,J)
      IF (J-1) 32,32,40
   32 JM1=J+1
      GO TO (30,60,70),KFY
   30 SIGM=1.
      SM=0.
      GO TO 100
   60 SIGM=-1.
      SM=2.
      GO TO 100
   70 CONTINUE
   40 JM1=J-1
      SIGM=1.
      SM=0.
      IF (JJ-J) 55,55,42
C TOP OR BOTTOM
   42 IF (K-9) 45,100,100
   45 IF (K-1) 20,100,46
   46 IF (K-3) 50,55,47
   47 IF(K-5) 50,55,48
   48 IF (K-7) 50,55,100
C TOP CONDITION
   50 JM1=J+1
      GO TO (30,60,70),KFY
C BOTTOM CONDITION
   55 JP1=J-1
      GO TO (130,160,170),KLY
  130 SIGP=1.
```

```
      SP=0.
      GO TO 141
  160 SIGP=-1.
      SP=2.
      GO TO 141
  170 CONTINUE
  100 JP1=J+1
      SIGP=1.
      SP=0.
  141 CONTINUE
      CSIGM=SIGM*C(I,JM1)+SM*C(I,J)
      CSIGP=SIGP*C(I,JP1)+SP*C(I,J)
      CSSIGM=SIGM*CSS(I,JM1)+SM*CSS(I,J)
      CSSIGP=SIGP*CSS(I,JP1)+SP*CSS(I,J)
      CALL CFEXP(I,J)
C LEFT OR RIGHT
      IF (K-10) 149,41, 33
  149 IF (K-9) 11,80,41
   11 IF (K-1) 241,33,12
   12 IF (K-4) 33,80,13
   13 IF (K-6) 80,34,34
C LEFT CONDITION
   33 GO TO (35,37,39),KFX
   35 CTEMP(I)= P2*C(I+1,J)+Q1*CSTAR(I+1,J)
      GO TO 65
   37 CTEMP(I)=P2*(2.*C(I,J)-C(I+1,J))+Q1*(2.*CSTAR(I,J)-CSTAR(I+1,J))
      GO TO 65
   39 CONTINUE
C RIGHT CONDITION
   34 GO TO (36,38,43),KLX
   36 CTEMP( I)=P3*C( I-1,J)+Q3*CSTAR( I-1,J)
      GO TO 75
   38 CTEMP(I)=P3*(2.*C(I,J)-C(I-1,J))+Q3*(2.*CSTAR(I,J)-CSTAR(I-1,J))
      GO TO 75
   43 CONTINUE
C INTERIOR CONDITION
   80 CTEMP(I)=P1*C(I,J)+P2*C(I-1,J)+P3*C(I+1,J)+P4*CSIGM   +P5*CSIGP
     1+Q1*CSTAR(I-1,J)+Q2*CSTAR(I,J)+Q3*CSTAR(I+1,J)+S1*CSSIGM+
     2S2*CSS(I,J)+S3*CSSIGP
      GO TO 85
C  LEFT CONDITION
   65 CTEMP(I)=CTEMP(I)+P1*C(I,J)+P3*C(I+1,J)+P4*CSIGM +P5*CSIGP +
     1 Q2*CSTAR(I,J)+Q3*CSTAR(I+1,J)+S1*CSSIGM+S2*CSS(I,J)+
     2S3*CSSIGP
      IB=1
      IN=2
      GO TO 85
C RIGHT CONDITION
   75 CTEMP( I)=CTEMP( I)+P1*C( I,J)+P2*C (I-1,J)+P4*CSIGM+P5*
     1  CSIGP  +Q1*CSTAR( I-1,J)+Q2*CSTAR( I,J)+S1*CSSIGM+S2*
     2CSS( I,J)+S3*CSSIGP
      GO TO 85
  241 CTEMP(I)=0.
      GO TO 85
   41 CTEMP(I)=C(I,J)
   85 CONTINUE
      DO 210 I=1,II
  210 C(I,J)=CTEMP(I)
  280 CONTINUE
      RETURN
      END
      SUBROUTINE CFEXP(I,J)
C SUB CFEXP
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION DCL(20,20),DCT(20,20)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
      COMMON/THIRD/P1,P2,P3,P4,P5,Q1,Q2,Q3,S1,S2,S3
      K=L(I,J)
      IF (K-10) 75,75,100
   75 CONTINUE
      DXSQ=DX*DX
      DYSQ=DY*DY
      DTX=DT/DX
      DTX2=DT/(DX*DX)
      DTY=DT/DY
      DTY2=DT/(DY*DY)
      P1=1.0+(A1-A2)*(U(I,J)*DTX+VY(I,J)*DTY)
      P2=A2*U(I,J)*DTX
      P3=-A1*U(I,J)*DTX
      P4=A2*VY(I,J)*DTY
      P5=-A1*VY(I,J)*DTY
      Q1=DCL(I,J)*DTX2+A4*U(I,J)*DTX
      Q2=-2.0*DCL(I,J)*DTX2+(A3-A4)*U(I,J)*DTX
      Q3=DCL(I,J)*DTX2-A3*U(I,J)*DTX
      S1=DCT(I,J)*DTY2 + A4*VY(I,J)*DTY
      S2=-2.0*DCT(I,J)*DTY2 + (A3-A4)*VY(I,J)*DTY
   10 S3=DCT(I,J)*DTY2-A3*VY(I,J)*DTY
      GO TO 200
  100 CONTINUE
  200 CONTINUE
      RETURN
      END
      SUBROUTINE CINPUT(JMIN,JMAX,ISET,JSET,KIN,T,TINPUT)
C SUB CINPUT
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      DIMENSION DCL(20,20),DCT(20,20)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
      COMMON/CN/CN1,CN2,CN3
C GIVES INPUT AT XMIN BETWEEN Y=JMIN AND Y=JMAX
C     WRITE (6,3000) CFX
 3000 FORMAT (' CFX=',F5.2)
      TDIFF=T-TINPUT
      KK=KIN
      IF (KIN-2) 9,100,150
    9 CONTINUE
      IF(T-TINPUT) 10,30,30
   10 DO 20 J=JMIN,JMAX
      C(ISET,J)=CFX
      CSTAR(ISET,J)=CFX
      CSS(ISET,J)=CFX
   20 CONTINUE
      GO TO 50
   30 CONTINUE
  435 DO 437 J=JMIN,JMAX
      C(ISET,J)=0.
      CSTAR(ISET,J)=0.
      CSS(ISET,J)=0.
  437 CONTINUE
      GO TO 50
  100 CONTINUE
      T1=43200.-DT
      T2=43200.+TINPUT
      IF (T-TINPUT) 110,130,101
  101 IF (T-T1) 50,110,102
  102 IF (T-T2) 110,130,50
  110 DO 120 J=JMIN,JMAX
      C(ISET,J)=CFX
      CSTAR(ISET,J)=CFX
      CSS(ISET,J)=CFX
  120 CONTINUE
```

```
      GO TC 50
  130 CO 140 J=JMIN,JMAX
      C(ISET,J)=0.
      CSTAR(ISET,J)=0.
      CSS(ISET,J)=0.
  140 CONTINUE
      GO TC 50
C     INSTRUCTICNS BELOW ARE FOR TOP INPUT
  150 CONTINUE
      IF (T-TINPUT) 160,170,170
  160 CO 165 I=1,7
      JSET=8
      C(I,JSET)=CN1
      CSTAR(I,JSET)=CN1
      CSS(I,JSET)=CN1
  165 CONTINUE
      CO 166 I=13,14
      JSET=9
      C(I,JSET)=CN2
      CSTAR(I,JSET)=CN2
      CSS(I,JSET)=CN2
  166 CONTINUE
      I=15
      JSET=8
      C(I,JSET)=CN3
      CSTAR(I,JSET)=CN3
      CSS(I,JSET)=CN3
      I=16
      JSET=7
      C(I,JSET)=CN3
      CSTAR(I,JSET)=CN3
      CSS(I,JSET)=CN3
      I=17
      JSET=6
      C(I,JSET1=CN3
      CSTAR(I,JSET)=CN3
      CSS(I,JSET)=CN3
      I=18
      JSET=6
      C(I,JSET)=CN3
      CSTAR(I,JSET)=CN3
      CSS(I,JSET)=CN3
      I=19
      JSET=8
      C(I,JSET)=CN3
      CSTAR(I,JSET)=CN3
      CSS(I,JSET)=CN3
      GO TC 50
  170 CO 175 I=JMIN,JMAX
      C(I,JSET)=0.
      CSTAR(I,JSET)=0.
      CSS(I,JSET)=0.
  175 CCNTINUE
   50 CCNTINUE
   60 RETURN
      END
      SUBRCUTINE OUTPUT(T,DTMAX)
C SUB CUTPUT
      DIMENSION C(23,21),CSTAR(23,21),CSS(23,21),U(46,34),VY(46,34)
      DIMENSION L(23,21)
      CIMENSION DCL(20,20),DCT(20,20)
      COMMON/ZEROTH/C,CSTAR,CSS,II,JJ,DT,DX,DY,DCL,DCT,L,
     1A1,A2,A3,A4,B1,B2,B3,KFX,CFX,KLX,CLX,KFY,CFY,KLY,CLY,
     2U,VY,ZP,GP,GPC,IFREQ,ICOUNT
C PRINT CCNCENTRATIONS IN BAY
      TH=T/3600.
      IF (II-11) 125,125,135
  125 CONTINUE
```

```
      GO TO 620
  610 WRITE(6,600) T
  600 FORMAT ('1',50X,'TIME= ',F11.4,' SECS*****')
      GO TO 630
  620 TH=T/3600.
      WRITE( 6,615) TH
  615 FORMAT ('1',50X,'TIME= ',F11.4,' HRS *****')
  630 CONTINUE
      WRITE(6,100)
  100 FORMAT (//30X,'C CONCENTRATIONS ARE')
      DO 440 J=1,JJ
  440 WRITE(6,400)  J,(C(I,J),I=1,II)
  400 FORMAT ( ' J=',I3,11E11.3)
      GO TO 2000
  135 CONTINUE
      GO TO 120
  110 WRITE (6,300) T
      GO TO 130
  120 WRITE (6,200) TH
  130 CONTINUE
      WRITE (6,111)
  111 FORMAT('0','          I=1         I=2         I=3         I=4         I=5
     1          I=6         I=7         I=8         I=9         I=10        I=1
     21')
      DO 150 J=1,JJ
  150 WRITE (6,250) J,(C(I,J),I=1,11)
  230 CONTINUE
      WRITE (6,112)
  112 FORMAT('0','          I=12        I=13        I=14        I=15        I=1
     16         I=17        I=18        I=19        I=20        I=21        I=2
     22')
      DO 160 J=1,JJ
  160 WRITE (6,250) J,(C(I,J),I=12,19)
  200 FORMAT ('1',40X,' C CONCENTRATIONS AT TIME T= ',F8.2,' HRS')
  300 FORMAT ('1',40X,' C CONCENTRATIONS AT TIME T= ',F8.2,' SECS')
  250 FORMAT (' J=',I3,11E11.3)
 2000 CONTINUE
   10 CONTINUE
      RETURN
      END
/*
//LKED.SYSIN DD *
      OVERLAY ALPHA
      INSERT  UNZON1
      OVERLAY ALPHA
      INSERT  UNZON2
      OVERLAY ALPHA
      INSERT  UNZON3,UNFLO,COEF,EXTRA,VFLOW,WTABLE,PSIVAL,PSIMID
      INSERT SINK,MATRIX,TENS,CK,CSL,HUMID,GRAPH,PINE,CURVE,PPLOT
      INSERT SCILQU,GROUP,MAT2,OUTRIT,TRAN
      OVERLAY ALPHA
      INSERT  OVLAN1
      OVERLAY ALPHA
      INSERT  OVLAN2,AVE,WAVE,RECV,HIDUR,LODUR,RQUAL,WRIT
      OVERLAY ALPHA
      INSERT  OVLAN3
      OVERLAY ALPHA
      INSERT  OVLAN4
      OVERLAY ALPHA
      INSERT  REC1
      OVERLAY ALPHA
      INSERT  REC2
      OVERLAY ALPHA
      INSERT  REC3
      OVERLAY ALPHA
      INSERT  GWBLCK,PHI,BOUND,TABLE,EQUIP,VEL,PREDIS,GWQUAL,VCALC
      INSERT TRIX,COEFX,TRIY,COEFY,EXPLIC,CINPUT,OUTPUT
/*
```

```
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT03F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT04F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT08F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT11F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT12F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT13F0[illegible] DD DSN=ALAN.APOPKA4,UNIT=2314,DISP=(,CATLG),
//    SPACE=(TRK,(20,5),RLSE),VOL=SER=USER01,DCB=(RECFM=VS,BLKSIZE=920)
//GO.FT14F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT15F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT16F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT17F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT18F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT19F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT20F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT21F001 DD UNIT=SYSDA,SPACE=(CYL,(2,1))
//GO.FT22F001 DD DSN=ALAN.APOPKA4,DISP=OLD,UNIT=2314,VOL=SER=USER01
//GO.SYSIN DD *
```

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